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FIELD MEASUREMENT AND MODEL EVALUATION
PROGRAM FOR ASSESSMENT OF THE ENVIRONMENTAL
EFFECTS OF MILITARY SMOKES

EVALUATION OF ATMOSPHERIC WIND FIELD AND DISPERSION MODELS FOR FOG-OIL SMOKE DISPERSION IN COMPLEX TERRAIN

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Three models used to predict the wind field and pollutant dispersion in complex terrain are compared with smoke dispersion data acquired as part of the AMADEUS field experiments in 1987 near Red Bluff, California. The models evaluated were WADOCT, HOTMAC/RAPTAD, and RAMS. The data base for model testing encompassed 7 fog-oil smoke releases from ground level under stable meteorological conditions. Smoke concentrations were measured out to 4 km downwind. Time-dependent meteorological and source data were available from these tests to be used as model input.

The results showed that the WADOCT model predicted quite well for the first 300 m downwind but then underpredicted the plume concentration by an order of magnitude at distances of 4 km downwind. The HOTMAC/RAPTAD model revealed a similar behavior. The inability of those two models to predict the trajectory of the plume and the observed limited vertical growth of the plume, in the downwind valley, are the likely causes of the underprediction. The RAMS model revealed very poor wind field and dispersion predictions based on the large grid spacing that was required (for this application) in order to make the computer run times manageable.

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FOREWORD

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A. J. Policastro 7/22/92
PI Signature Date

EXECUTIVE SUMMARY

Three wind field/dispersion models (the WADOCT, HOTMAC/RAPTAD and RAMS models) are tested with field data from 7 stable fog-oil smoke dispersion releases in complex terrain obtained from the AMADEUS Dispersion Experiments. The AMADEUS Dispersion Experiments were carried out at the Meadowbrook Site, in northern California, during Phase IV of Project WIND. The purpose of this report is to evaluate the performance of the most promising complex terrain dispersion models (which cover the range of simple to complex modeling approaches) for the distance scales on the order of 25 m to 4 km.

The WADOCT model, with the simplest modeling approach, predicted quite well for the first 300 m downwind but then underpredicted the plume concentration by an order of magnitude at distances of 4 km downwind. The HOTMAC/RAPTAD model (a significantly more detailed model than WADOCT) results were similar to those of the WADOCT model. The likely causes of the underpredictions of both the WADOCT and HOTMAC/RAPTAD models are the models' inability to predict the trajectory of the plume and the observed limited vertical growth of the plume, in the downwind valley. The most detailed model, the RAMS model, produced poor wind field and dispersion predictions due to the large grid spacing that was required (for this application) in order to make the computer run times manageable. It is hoped that a version of RAMS that is currently in a developmental phase will be able to more adequately handle these trials.

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1. INTRODUCTION

In the Fall of 1987, a team of researchers from the University of Illinois (UIUC) and Argonne National Laboratory (ANL) undertook a series of smoke dispersion trials at a complex terrain site (the Meadowbrook Site) in Northern California as part of a larger program to develop an improved model for smoke dispersion. This work was carried out under the sponsorship of the US Army Biomedical Research and Development Laboratory (USABRDL). In addition, these field trials were performed in cooperation with researchers from several organizations working under contract to the US Army Atmospheric Sciences Laboratory (ASL) located at White Sands Missile Range, New Mexico. The dispersion trials discussed herein actually represent only a small part of the total ASL effort which had as its major objective the validation and improvement of certain of the wind field models developed by ASL. This larger effort, known as Project WIND, involved four major field studies; the dispersion trials of interest here were carried out during the fourth such study. In the terminology of Project WIND, the field studies described herein are known as the AMADEUS Dispersion Experiments carried out at the Meadowbrook Site during Phase IV of Project WIND.

The field dispersion effort done by UIUC and ANL during the AMADEUS Dispersion Experiments represents the most detailed field work in a series of dispersion studies done by these groups. In 1985, UIUC and ANL carried out a field dispersion study at Dugway Proving Ground, where dispersion in simple terrain and simple meteorology was studied (Liljegren, 1988). In 1987, UIUC and ANL undertook a field dispersion study at Camp Atterbury, where dispersion in simple terrain and complex meteorology was studied (Liljegren, 1989). Model/data comparisons were performed with the field data at Dugway and at Camp Atterbury (Policastro, 1989; and Policastro, 1991). The AMADEUS Dispersion Experiments represent a study under conditions of complex terrain and complex meteorology.

The Meadowbrook Site is located approximately 20 miles east of Red Bluff, California in the foothills of the Sierra-Nevada Mountains, and consists of a forked creek valley with surrounding slopes rising to a height of about 250 m above the valley floor. The meteorology of the site is dominated by a density-driven, diurnal upslope-downslope flow pattern typical of mountain/valley topography. The field data include average concentration measurements on five or six transects (depending on the trial) out to distances of about 4 km. In addition, the data base includes time-averaged source

measurements as well as meteorological data from thirteen 10-m instrument towers, a 30-m tower and a 2-m mast.

The meteorology and the fog-oil concentration measurements are similar among the various stable trials. Concentration data used and presented here have been updated from previously reported values (DeVaull, 1990) to account for variations of oil loss with dosage and time spent in the cassette. Previously reported values assumed a uniform oil loss, and closer examination of the data showed this assumption to be poor.

This report provides an evaluation of the more popular and promising complex-terrain wind field/dispersion models with the stable AMADEUS field data. The model selection criteria included using a model that would both apply to the stable AMADEUS dispersion data and could be set up and run in less than 3-man months of effort. Models that were considered to be applicable to the stable AMADEUS dispersion data included those that were able to: (1) handle complex terrain; (2) produce concentration predictions on the time scale of less than 1 hour and a distance scale of about 25 m - 4 km downwind from a source; and (3) produce concentration predictions for receptors that were lower in elevation than the source. The WADOCT, HOTMAC/RAPTAD, and RAMS models represent the state-of-the-art wind field/dispersion models that met all of the model selection criteria. In addition, the WADOCT, HOTMAC/RAPTAD, and RAMS models cover the range of simple to complex modeling approaches, respectively.

Each of the three models predicts the wind field first, from which smoke dispersion is computed. The WADOCT model treats the release as a Gaussian plume which is transported and dispersed downwind with a horizontally-uniform wind speed. The HOTMAC/RAPTAD Model and the RAMS Models are complex finite-difference solutions to the governing primitive equations for flow in complex terrain with complex dispersion models added to the wind field models. The HOTMAC/RAPTAD Model employs the hydrostatic and Boussinesq approximations and is a less complex model than RAMS. The WADOCT Model runs on a PC whereas the HOTMAC/RAPTAD and RAMS Models require computer workstations. The WADOCT model predictions were compared with all 7 stable releases, and the HOTMAC/RAPTAD models were compared with data from two trials.

The purpose of the model evaluation portion of the current research program is three-fold: (1) to identify the strengths and weaknesses of the existing modeling approaches; (2) to define the level of model performance which can be expected given the current state of the art; and (3) to provide baseline accuracy from which a PC model (to be developed later as part of the current research program) can be compared and from which improvements can be made. Based on the experience gained, the PC model can be developed and validated with the field data. Such a validated model can be used by the Army in two ways:

(a) A validated model can aid in assessing the potential environmental and health effects associated with smokes used in training exercises in complex terrain. Of greatest interest here is the prediction of dosages (time-integrated concentrations), particle-size distributions, and deposition rates out to several kilometers from the source.

(b) A validated modei can also be used in the planning and execution of training exercises at the facilities where smoke is used in complex terrain. In this application, predicting the downwind extent of the visible plume is also an important consideration.

In Section 2 below, we present the key features of the three wind field/dispersion models considered for evaluation. Then, in Section 3, we briefly summarize the AMADEUS field study. At that point we present the model/data comparisons in Section 4 and, finally, summarize the main conclusions of the work in Section 5.

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2. THE MATHEMATICAL MODELS

2.1 Introduction

The choice of mathematical models for evaluation in this report was based on:

(a) the appropriateness and availability of computer models for the prediction of complex terrain wind flows and dispersion for plumes dispersing within several kilometers from a ground-level source, and

(b) the desire to test models of different theoretical development and complexity in order to determine which approach is likely to provide the greatest accuracy. It is also useful to determine the comparative accuracy of simple models that run quickly on PC's as compared to those models that require considerable computer resources.

Since a PC model is being developed for ground-level smoke releases as part of the current project, it is important to learn from the performance of existing models with the AMADEUS data. In addition, the performance of existing models with the AMADEUS data can provide a yardstick by which the accuracy of the PC model (currently under development) can be judged.

The criteria used in the model selection included a model that would both apply to the stable AMADEUS dispersion data and could be set up and run in less than a few man-months of effort. Models that were considered to be applicable to the stable AMADEUS dispersion data included those that were described to be able to: (1) handle complex terrain; (2) provide detailed plume predictions on the time scale of less than 1 hour and a distance scale of about 25 m - 4 km downwind from a ground-level source; and (3) produce concentration predictions for receptors that were lower in elevation than the source. A review of the literature and discussions with many model developers revealed that most dispersion models do not apply to these data, for a variety of reasons. For example, it was determined that most complex terrain dispersion models apply to mesoscale flows and dispersion (Kunkel and Izumi, 1990). Such models do not account for the physics of small-scale dispersion and require grid sizes that are much too large to lead to meaningful predictions for our smoke plumes. Other models such as the U.S. Department of Energy's models MATHEW/ADPIC (Rodriquez et al., 1992), were excluded from the study because of the large amount of effort that is required to make these models operational. Another set of candidate models were excluded because of the lack of a complex terrain feature. These models

included all three models used in the Dugway modeling report (Policastro et al., 1989) and the Camp Atterbery modeling report (Policastro et al., 1991), e.g. the INPUFF model (Petersen, 1984), the BEAR model (Ludwig, 1977) and the RIMPUFF model (Thykier-Nielsen and Mikkelsen, 1987). Similar simple meteorology, flat terrain models such as the U.S. Environmental Protection Agency's (U.S. EPA's) TRIAD model (U.S. EPA, 1990) and NOAA's ALOHA model (NOAA, 1991) were also deemed inapplicable because of the lack of a complex terrain feature. EPA's CTDMPLUS (EPA, 1990) was excluded from the study due to the fact that it is not valid for modeling drainage flow. Models developed by the Atmospheric Sciences Laboratory (ASL) at the White Sands Missile Range in New Mexico were not available to us but may, in the future, be used to compare with the AMADEUS data by the developers at ASL. A complex terrain model (wind field and dispersion model) by Dr. Frank Ludwig of the Stanford Research Institute was made available to us, but the coding for the linkage between the separate wind field and dispersion codes had not yet been prepared. We considered that model incomplete. The combination of the LINCOM (wind field model) and the RIMPUFF model developed at Risø National Laboratory (Thykier-Nielsen and Mikkelsen, 1988) was also considered, but was excluded based on a limitation of modeling low wind speeds.

In consideration of the above requirements, our search for appropriate models revealed that only three available models could be identified that could handle the AMADEUS data sets. They are:

(1) The WADOCT model, a PC model that predicts a wind field and dispersion field by means of a time-dependent release of Gaussian puffs. This model was developed by the US Air Force for the determination of the fate of chemical spills in complex terrain. Some previous testing with the AMADEUS data was carried out by the developers of that model (Kunkel and Izumi, 1990).

(2) The HOTMAC/RAPTAD model, a three-dimensional hydrodynamic and diffusion model (Yamada et al., 1992) that requires a computer workstation for its execution. The code does not yet have a version that runs in a PC environment. The HOTMAC wind field model provides a second-order closure solution to the basic flow equations using the hydrostatic and Boussinesq assumptions. The RAPTAD code is a Lagrangian puff-diffusion model based on a Monte-Carlo statistical process. The model was originally developed at Los Alamos National Laboratory by Dr. Ted Yamada and his associates with later improvements in the code and user interface by Dr. Yamada at Yamada Science and Art.

(3) The RAMS model (Walko and Trembeck, 1991) is a finite-difference atmospheric model that is constructed from the full set of primitive dynamical equations which govern atmospheric motions. The model is presented by the authors as highly versatile, capable of handling mesoscale and small-scale dispersion in complex terrain and even thunderstorm activity. The development of the model using the full primitive equations should provide more accuracy than the HOTMAC/RAPTAD model which makes the Boussinesq and hydrostatic approximations. For this evaluation, the RAMS model was run on an engineering workstation. A PC version is not available.

Since the WADOCT, HOTMAC/RAPTAD, and RAMS models were the only operating models available to us, we accepted all three for this evaluation. It is fortuitous that the set of three models represents a set of models of increasing complexity from the simple PC model of WADOCT to the very complex model of RAMS (full solution of the primitive equations).

2.2 The WADOCT Model

WADOCT (Wind and Diffusion Over Complex Terrain) is a complex terrain wind and dispersion model that runs on a microcomputer. It consists of two separate models: (a) AFWIND, a surface-layer wind flow model based on the high resolution wind (HRW) model developed by Army scientists at ASL, and (b) AFTOX, a Gaussian puff dispersion model. The terrain induced wind field and the dispersion pattern are computed separately and independently of each other. This means that plume dispersion predictions using AFTOX do not require any input from AFWIND and vice versa. Once these models are computed separately, a transformation scheme is then used to take the location and shape of the predicted plume and adjust it to the computed wind field. Additional information on the development of this model is available from Lanicci (1985), Lanicci and Weber (1986), Lanicci and Ward (1987), and Kunkel (1988a and 1988b).

The wind flow model is essentially an inviscid solution to the momentum equations including only the acceleration, advection, and buoyancy terms (no turbulence terms). The model surface layer is divided into "flux boxes" of surface normal thickness of 10 m, conforming to the warped terrain surfaces. The terrain-following coordinate system is used to include effects of terrain slopes in the calculations. By minimizing the overall acceleration over the entire flow domain, it operates by shifting the initial

wind vectors until they balance the local buoyancy forces. AFWIND is thereby a pure upslope/downslope model which neglects drag, shear, mechanical pressure, mass conservation, and the larger-scale temperature gradients (Kamada, 1989). The obtained solution of the AFWIND equations is not necessarily unique and convergence to the true minimum is not assured. A local minimum may be achieved which has no clear physical meaning. In fact, the wind field may not resemble the measured flow due to the non-uniqueness in the solution obtained (Kamada, 1989).

The diffusion part of the model is the AFTOX model, a Gaussian puff/plume model designed to handle continuous and instantaneous releases. The Gaussian puff model uses an equation to describe the dispersion of a puff with time. The puff equation assumes that the material is conserved during transport and diffusion, an assumption that is valid for the particulate phase for smoke applications. The distribution of concentration within the puff is assumed to be Gaussian.

Once the wind field has been determined and the concentration contours have been predicted (based on the calculation of a horizontally homogeneous wind field), the points along the contours are then repositioned as the conversion is made from the Gaussian coordinate system to a wind flow coordinate system.

It should be clear that this method of melding together the wind field and plume dispersion predictions is very approximate and can lead to inconsistencies between the resulting wind and dispersion fields. If the wind field shows a convergent section due to constraining terrain, the plume dispersion may yield a much wider plume than is indicated by that wind field because only a horizontally uniform wind speed is input into the dispersion calculations. The tradeoff in the WADOCT model is between technical accuracy for ease of computation. The model/data comparisons shown later will be an indication of the success of the approach.

2.3 The HOTMAC/RAPTAD Model

The HOTMAC portion of the model is able to predict three-dimensional distributions of wind speed, wind direction, turbulence, temperature and water vapor. The basic equations for HOTMAC are the conservation equations for mass, momentum, internal energy, mixing ratio of water vapor, and turbulent kinetic energy (Yamada and Bunker, 1988). A detailed description of the model equations, boundary conditions, and

numerical scheme is given by Yamada and Bunker (1988). HOTMAC is a second-order turbulence closure model based on a set of second-moment turbulence equations closed by assuming certain relationships between unknown higher-order turbulence moments and the known lower-order moments. HOTMAC can be used under quite general conditions of flow and thermal stratification. The model assumes hydrostatic equilibrium and uses the Boussinesq approximation. Therefore, in theory, the model applications are limited to flows where the local acceleration and advection terms in the equation of vertical motion are much smaller than the acceleration due to gravity (hydrostatic equilibrium) and temperature variations in the horizontal directions are not too large (Boussinesq approximation). The effect of the hydrostatic approximation is that the vertical profiles of pressure are wholly due to thermally induced density differences; i.e., it assumes the atmosphere is hydrostatic and ignores advection, acceleration, and drag in the vertical momentum equation. This is reasonable for shallow slopes, higher stabilities and grid spacing larger than a few kilometers. The assumption is less accurate for grid spacing on the order of 300 m as would be needed for our AMADEUS model/data comparisons.

Surface boundary conditions are constructed from the empirical formulas of Dyer and Hicks (1970) for nondimensional wind and temperature profiles. The temperatures in the soil layer are obtained by solution of the heat-conduction equation. Appropriate boundary conditions are the heat energy balance at soil surface and the specification of soil temperature at a certain depth. The lateral boundary values are obtained by integration of the corresponding governing equations, except that variations in the horizontal directions are neglected.

An initial wind profile at a reference site in the computational domain is first constructed with the assumption of a logarithmic variation from the ground (if actual data are not available) up to a level where the wind speed reaches a measured ambient value. Initial wind profiles at other grid locations are obtained from the initial wind profile determined above and a mass conservation equation. Routines also exist to estimate the initial potential temperature profile, the initial turbulence kinetic energy and length scale.

RAPTAD is a Lagrangian puff code based on the Monte Carlo statistical diffusion process. The center location and standard deviation of concentration distribution for each puff are computed by use of wind and turbulence values generated by HOTMAC.

Then the concentration at any location is computed by summing of concentrations contributed by all the puffs. RAPTAD can be used under extreme conditions with highly heterogeneous wind and turbulence distributions where a conventional Gaussian plume model may fail.

One disadvantage to HOTMAC/RAPTAD (and also RAMS) is the need for many more input parameters than is needed by WADOCT. For HOTMAC/RAPTAD, information on such items as soil/vegetation moisture is necessary and would have to be approximated or estimated.

2.4 The RAMS Model

RAMS (Regional Atmospheric Modeling System) is a very versatile numerical code developed at Colorado State University and ASTeR, Inc. for simulating and forecasting meteorological phenomena and for plotting the results. RAMS has three major components:

(a) an atmospheric model that predicts the wind flow and plume dispersion,

(b) an isentropic analysis package which prepares initial data for the atmospheric model from observed meteorological data, and

(c) a post-processing model visualization and analysis package which interfaces atmospheric model output with a variety of visualization software utilities.

The atmospheric model is constructed around the full set of primitive dynamical equations which govern atmospheric motions, solar and terrestrial radiation, moist processes including the formation and interaction of clouds and precipitating liquid and ice hydrometeors, sensible and latent heat exchange between the atmosphere, multiple soil layers, and a vegetation canopy, the kinematic effects of terrain, and cumulous convection. The model may be configured to cover an area as large as a planetary hemisphere for simulating mesoscale and large atmospheric systems. On the other hand, the documentation states that there is no lower limit to the domain size or to the mesh cell size of the model's finite difference grid. Microscale phenomena such as tornadoes and boundary layer eddies have been simulated with this code as well. Current research with RAMS includes atmospheric scales ranging from large

eddy simulations (horizontal grid spacing = 100 m) to synoptic simulations of convective systems (horizontal grid spacing = 100 km).

Unlike HOTMAC/RAPTAD, RAMS includes non-hydrostatic terms in the prognostic primitive equations. This allows greater accuracy in such applications as to steep, small-scale slope flows in complex terrain. RAMS also treats the sub-grid scale density fluctuations neglected in the mass budget of HOTMAC. The more detailed formulation with RAMS has a disadvantage in that greater run times are required in order to handle the more complex physics. One difference among the three models is that WADOCT produces a single steady-state wind field that is not updated as a function of time as the wind data change. As a result, for WADOCT, the model results become less relevant as transport time increases because the assumed steady state wind field gradually loses validity. The HOTMAC/RAPTAD and RAMS models predict time-dependent wind fields that are fed directly into a time-varying pollutant dispersion model.

As an example of the computer requirements needed by these models, for our types of cases, the WADOCT model can be run on a 386-based microcomputer. The HOTMAC/RAPTAD models require a workstation, and the RAMS model requires a supercomputer or a high-end workstation.

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3. THE AMADEUS FIELD STUDIES

3.1 Introduction

The AMADEUS Dispersion Experiments produced a large amount of valuable data on dispersion in complex terrain. Two sets of dispersion experiments were actually conducted. In addition to the 12 fog-oil smoke trials of primary interest here, 11 tracer releases were also made. The tracer gas was sampled over a larger but more sparse grid than was the smoke. The fog-oil smoke was collected using filter samplers operated over the full duration of the trial and was simultaneously sampled every second using an optical device. Figure 3.1 shows the Meadowbrook site and sampling grid, including fog-oil sampler transect locations and meteorological tower locations. The smoke concentration was measured at heights of 2 and 8 m using filter samplers located on 8 m masts (see Figure 3.2 and Figure 3.3). Depending on the trial, 30 to 40 locations were used for sampling the smoke. A majority of the information presented in this section is extracted from a companion report (Brown, 1990).

A complex array of instruments (as shown in Figure 3.1) was used to determine the atmospheric conditions during each dispersion trial as identified below.

1. Fourteen surface stations were used to map the horizontal variation of the surface winds over the complex terrain site. Thirteen of these stations were 10-m masts equipped with cup anemometers and direction vanes at the 10-m level. In addition, the 30-m tower identified in Item 2 below was instrumented with cup anemometers and direction vanes at the 10-m and 30-m levels, thus providing one additional 10-m surface wind measurement and a corresponding wind measurement at 30 m. Except for the 30-m tower, all of the surface stations include temperature measurements at the 10-m level, and eight of the these stations also provide temperature measurements at the 2-m level. Moreover, temperature measurements at the 2-m, 8-m and 30-m levels were used to augment the wind speed and direction data on the 30-m tower.

2. A micrometeorological tower was used to determine vertical profiles of wind and temperature to a height of 30 m and to provide indirect measurement of atmospheric stability through the fluctuations in the wind velocity and temperature. This tower was instrumented with propeller anemometers (three independent directions) and temperature sensors at five levels: 2-m, 4-m, 8-m, 16-m and 30-m.

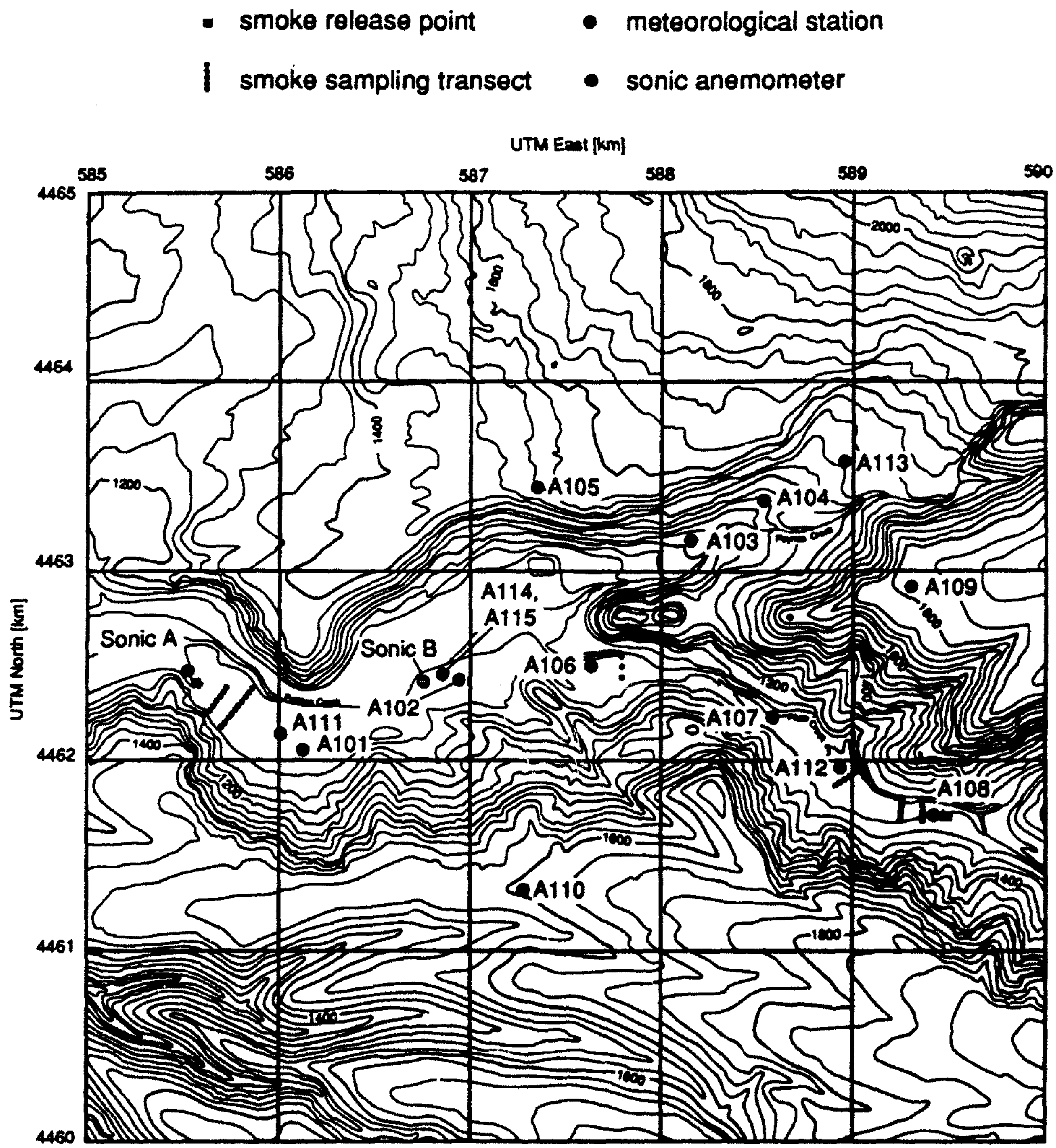


Figure 3.1 Topographical map of the Meadowbrook Site. Elevations are in feet above sea level with contour lines at increments of 40 feet. The horizontal scale is in Universal Transverse Mercator coordinates, with the grid marked in km. The topographical information is taken from the USGS map of Inskip Hill, California.

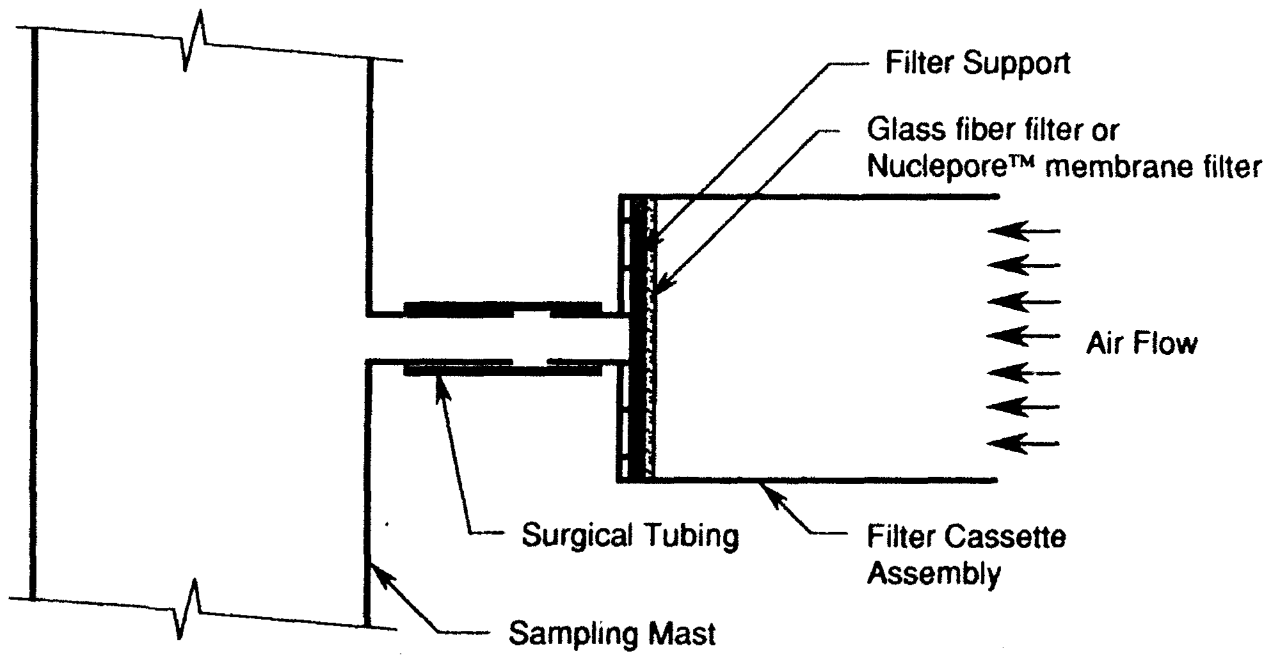


Figure 3.2 Schematic Illustration of the Filter Cassette Assembly.

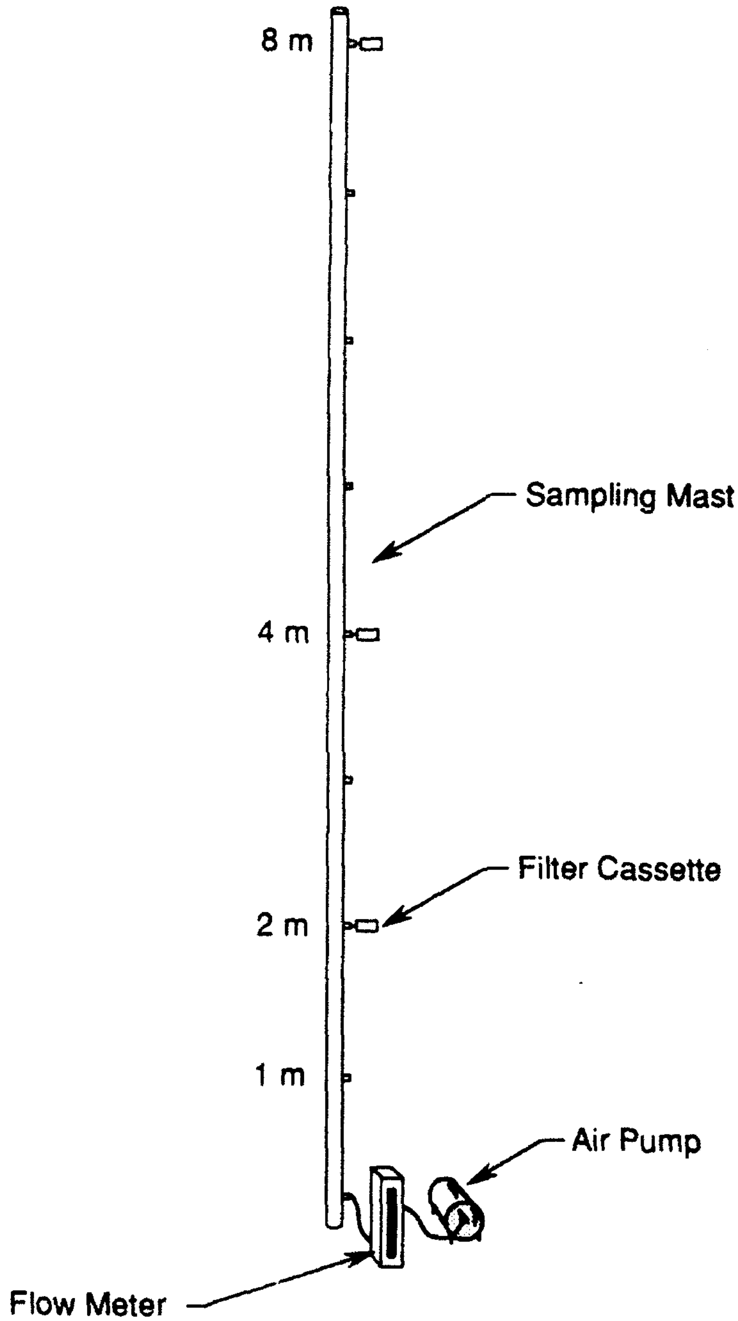


Figure 3.3 Illustration of the Sampling Mast/Air Pump Assembly.

3. Two sonic anemometers were used to directly measure the vertical momentum and heat flux through the atmospheric boundary layer and thus provide additional data useful in characterizing atmospheric stability.

4. Instrumented balloons were used to provide wind and temperature profiles to a height of several kilometers and thus allow the thickness of the atmospheric boundary layer to be determined.

5. A mini-sodar which employs reflected sound waves was used to characterize the atmospheric boundary layer to a height of roughly 300 m.

In addition to the meteorological data, the following data are available as part of the AMADEUS data base.

1. Source data providing time histories of the smoke release rates.

2. The time-averaged smoke concentration data collected at 2 m and 8 m using filter samplers.

3. The instantaneous smoke concentration data obtained using aerosol photometers.

4. More than 250 aerial photographs of the smoke plume taken during all but the 2 nighttime smoke releases.

3.2 The Test Site and Sampling Grid Layout

The Meadowbrook site is located approximately 20 miles east of Red Bluff, California in the foothills of the Sierra-Nevada Mountains, and consists of a forked creek valley with surrounding slopes rising to a height of about 250 m above the valley floor (as shown in Figure 3.1). These slopes are covered with deciduous and coniferous trees reaching heights of 25 m, although the average height of the surrounding forest is about 8 to 10 m. The valley is formed by the joining of Plum Creek with Payne Creek in the relatively flat, clear floor area which is about 800 m across at its widest point. These two creeks flow down from the higher elevations east of the valley. The cleared area paralleling each of the two creeks narrows and eventually vanishes as elevation increases in each of the two branches of the creek fork.

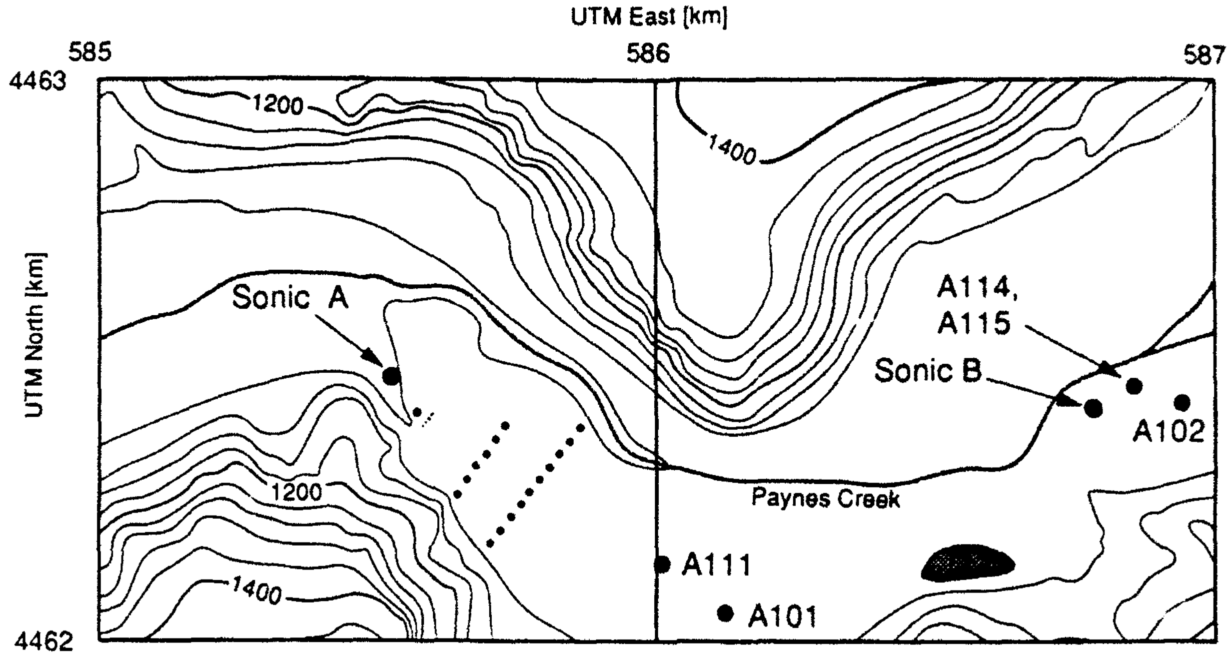
The meteorology of the site is dominated by a density-driven, diurnal upslope-downslope flow pattern typical of mountain/valley topography. The elevation drops about 350 m over a distance of roughly 10 km from east to west. At night, colder,

denser air flows down the mountain slopes into the valley; during the day, warmer, lighter air flows up the slopes from the valley floor. Mesoscale effects also influence the meteorology of the site. The Boise-Cascade Mountains to the west of the site block much of the moist air from the Pacific Ocean thus giving rise to an extremely dry local climate. As a result, daytime heating of the ground is intense with temperatures of 40 °C common in the valley floor. Nighttime cooling is equally strong with temperatures below 10 °C possible in the lower areas of the test site. The meteorology of the test area is well established, both through the nature of the terrain and through three previous large-scale wind-field studies carried out in Phases I–III of Project WIND.

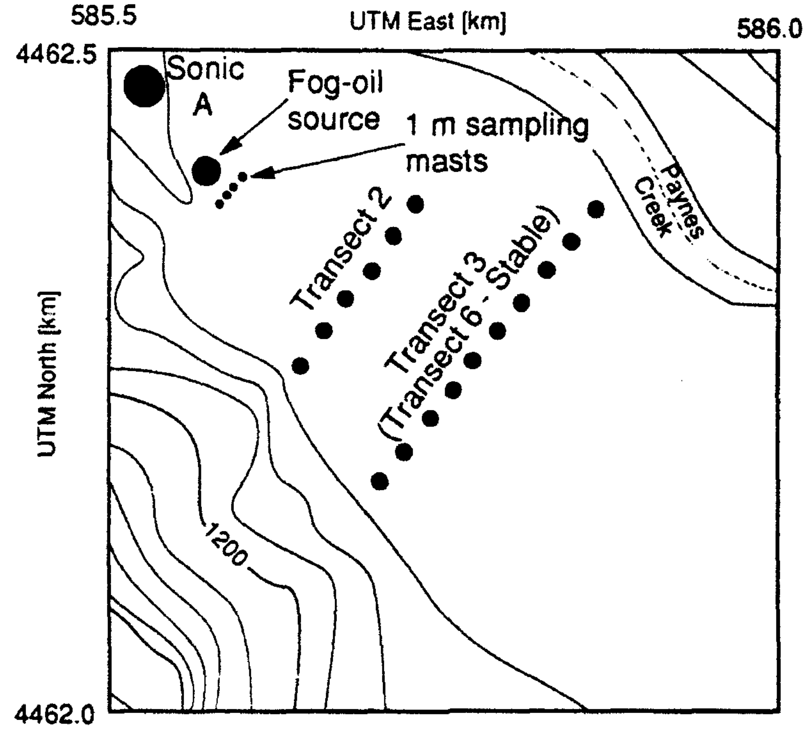
To take advantage of these diurnal wind characteristics, two smoke release locations and associated sampling grids were established. One, known as the unstable release point, is located at the west end of the valley floor as shown in Figure 3.4. This release point was used for daytime experiments when upslope winds were anticipated. The unstable designation comes from the fact that a highly convective, unstable atmospheric boundary layer is expected under these conditions. The second location, known conversely as the stable release point, lies in the upper reaches of the cleared area of the Plum Creek valley and is shown in Figure 3.5. This location was used for the nighttime and early morning smoke releases when downslope winds and a stable atmospheric boundary layer were anticipated. For the purpose of this report, we are primarily concerned with the releases from the stable release point. As is evident in Figure 3.5, Transect 1 is approximately 25 m downwind from the release point, while Transect 2, 3, 4, 5 and 6 are approximately 130 m, 250 m, 600 m, 2 km, and 4 km from the release point, respectively.

Near the stable release point, the wind follows the gradient of the terrain quite well. The smoke dispersion was very sensitive to the local stability and surface roughness. Five rows of samplers spanning the width of the creek valley and covering a downwind distance to 2 km were used to sample the smoke released from this location as shown in Figures. 3.1 and 3.5. In a few of the tests, samplers located on the unstable-release-point grid were also operated to give a total sampling distance of more than 3 km.

In total, twelve smoke releases were made: five from the unstable release point and seven from the stable release point. The trials ranged from 12 to 67 minutes in duration with the majority of the releases lasting between 30 min and one hour. Three of



(a)



(b)

Figure 3.4 Close-up views of the "unstable" test area showing (a) locations of relevant meteorological instrument towers and (b) enlarged view of the sampling transects. The horizontal scale is in Universal Transverse Mercator coordinates, with the grid marked in km. Elevations are in feet above sea level with contour lines at increments of 40 feet The topographical information is taken from the USGS map of Inskip Hill, California.

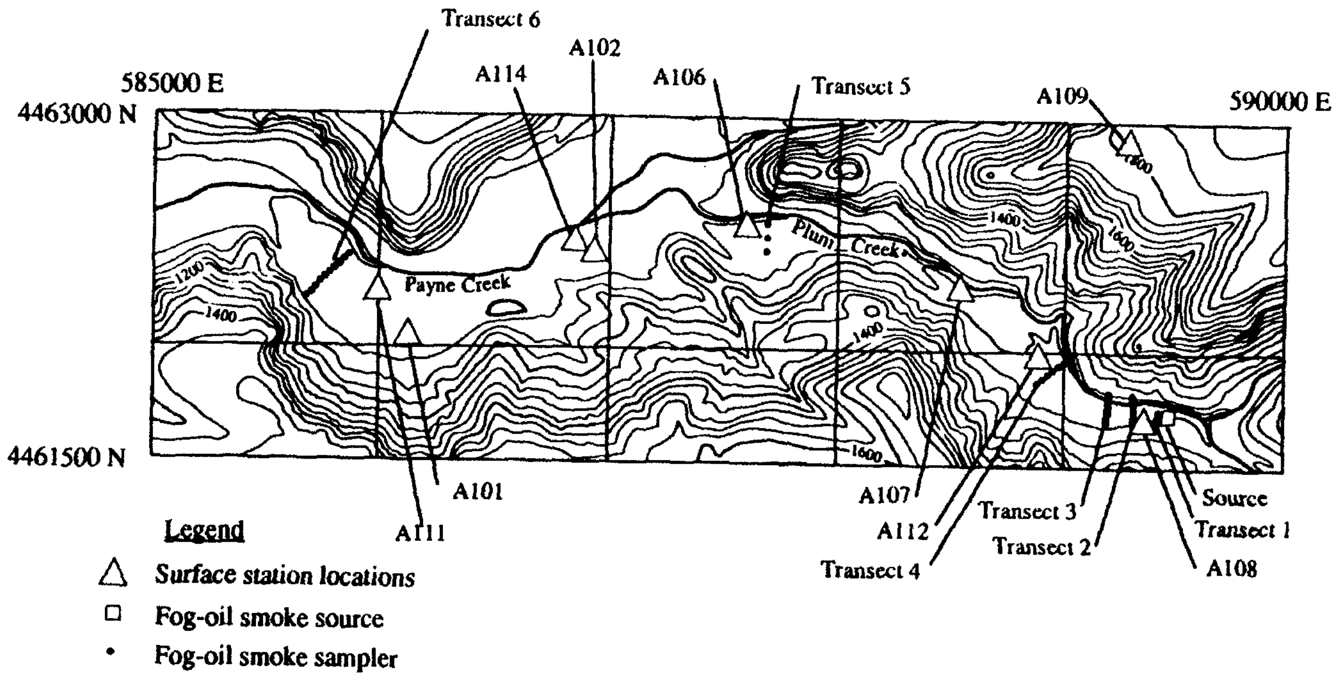


Figure 3.5 Map of the sampler locations for the stable dispersion tests. The sampling transects, meteorological towers, and source location are shown. Elevations are in ft above sea level with contour lines at increments of 40 ft. The horizontal scale is in Universal Transverse Mercator coordinates, with the grid marked in km. The topographical information is from a USGS map of Inskip Hill, California.

the trials were conducted under clear skies; the remaining four were carried out under partly cloudy conditions.

3.3 Meteorological and Source Measurements (Surface Stations)

During the AMADEUS dispersion experiments, thirteen 10-m surface stations equipped with cup anemometers and direction vanes were used. The 10-m surface stations measured the wind speed, wind direction and temperature at a height 10 m above the ground. A second temperature measurement at a height of 2 m was also made at the surface stations in order to determine the vertical temperature gradient (lapse rate) near the ground. In addition, a 30-m micrometeorological instrument tower was located in the center of the valley floor. Cup anemometers and direction vanes were mounted on this tower at the 10-m and 30-m levels. The 30-m tower was also equipped with propeller anemometers (which measure the three components of the wind vector) at the 2-m, 4-m, 8-m, 16-m and 30-m levels. Thus, a total of 14 surface wind-field measurements were made at the 10-m level and one additional measurement was made at the 30-m level, giving 15 measurements in all. Figure 3.1 shows the locations of the 14 meteorological stations. Appendix A summarizes the meteorological conditions at all 14 meteorological stations for each of the stable releases.

Fog-oil release rates were recorded with respect to time. For the purposes of this report, average release rates were used. Table 3.1 summarizes the source and meteorological conditions of the stable releases.

3.4 Concentration Measurements

The fog-oil smoke was collected on aspirated filter samplers mounted at 2-m and 8-m levels, as shown in Figure 3.2. The fog-oil data are based on the total mass of oil in the proper molecular weight range collected on the filters. These data, combined with the aspiration rate through the filter and the release time, are used to determine average concentration.

Trials 0927871 and 0927872 were unique in that the same filter samplers collected fog-oil for both trials. Therefore, the calculated dosage for these trials reflects data for both tests.

Table 3.1 Source and Meteorological Data for the Stable AMADEUS Smoke Dispersion Experiments.

Trial No.	Start Time	Release Time [min]	Release Rate [g/s]	Wind Speed* (m/s)	Variation in Temp** (°C)
0925871	00:18	45	40.4	1.9	1.0
0927871	03:19	20	44.5	1.8	2.2
0927872	06:44	10	34.7	2.5	1.9
0930871	06:48	40	40.4	2.3	2.7
1001871	06:52	40	29.9	2.7	2.1
1002871	07:17	30	40.8	1.9	2.2
1003871	06:56	31	28.2	3.0	1.0

* Wind speed is measured at 10-m Surface Station A108, which is near to source.

** Temperature difference between 2-m and 8-m levels at 10-m Surface Station A108.

Average concentration data used and presented here have been updated from previously reported values (DeVaull, 1990) to account for variations of oil loss with dosage and time spent in the cassette. Previously reported values assumed a uniform oil loss, and closer examination of the data showed this assumption to be poor. (See Appendix B for details on this updated data.)

To place the model/data comparisons in proper perspective, we need to set error bounds on the measured concentration values. The two factors which enter into this determination are (a) uncertainty in the experimental procedures and (b) the natural variation of the atmosphere. A careful analysis of experimental methods provides an uncertainty of roughly a factor of 1.4 at the 95 % confidence level. Major contributors to this experimental uncertainty are (a) oil loss during the period between collection and chemical analysis, (b) uncertainty in the aspiration rate, and (c) errors in the mass determination by gas chromatography. These errors can, in principle, be reduced by better experimental techniques. On the other hand, the natural variation of the atmosphere is inherent in the temporal and spatial inhomogeneity of the smoke plume itself. Instantaneous data acquired simultaneously with filter sampling reveals that the

standard deviation of the concentration measured at a particular location over the duration of a trial is roughly 5 times the mean value. This uncertainty can be reduced only through ensemble averaging. Since the filter samplers approximate an arithmetic average of the instantaneous data, conventional statistics provides an error estimate for the arithmetic mean or average concentration of roughly 1.6 at the 95 % confidence level. Combining these two independent effects, we can estimate that the uncertainty in the results of a single trial is roughly a factor of two at the 95 % confidence level.

Additional details concerning the experimental procedures and the associated uncertainties in the concentration data are given in the three companion reports by Liljegren et al. (1989), DeVaull et al. (1989) and DeVaull et al. (1990).

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4.0 COMPARISON OF MODEL PREDICTIONS WITH THE AMADEUS FIELD DATA

4.1 Preparation of Model Inputs

All three models required different sets of input parameters, owing to their differences in theoretical approaches and modeling assumptions. In this subsection, the various input parameters are presented for the various models.

4.1.1 WADOCT

A copy of the WADOCT computer code was obtained through the Air Force Geophysics Laboratory, at Hanscom AFB, MA., and input files were prepared in consultation with the User's Guide. Four critical types of input were required for the WADOCT model: (1) terrain data, (2) vegetation data, (3) meteorological data, and (4) source data.

Both terrain and vegetation information were provided in detail for a 5-km by 5-km area in the vicinity of the stable release point, with elevations/heights provided every 100 m in both the North-South and East-West directions. Meteorological information was provided from the surface stations, with input data for wind speed, wind direction, standard deviation of wind direction, and vertical temperature gradients. Wind speed, wind direction, and temperature profile data were all from meteorological stations A106, A107, A108 and A112. These stations were used since they were in line with the dispersing fog-oil. The standard deviation of the wind direction was determined with a 2/3 weighting of station A108 and 1/3 weighting of station A112. For Trial 0930871, model/data comparisons are provided for a simulation that utilized only station A108 wind speed and wind direction as input and a run where 12 of the 10-m surface stations were used for wind speed and wind direction.

Since WADOCT does not allow for time-dependent meteorological conditions, time dependent release rate data input would have been meaningless. Furthermore, WADOCT does not allow for a time dependent source. Therefore source release rate data were provided to the model as a release rate that was averaged over the duration of the trial.

While WADOCT was run for all seven stable releases, only one set of concentration data is presented for Trials 0927871 and 0927872. These two trials are presented together, since the fog-oil was collected for both of these two tests on one set of filter samplers. WADOCT predictions were actually made for both of these trials, but the predicted concentrations were then combined in order to perform comparisons.

The release height was chosen to be 3 m above the ground for all of the AMADEUS trials since that was the observed height of the center of the initial smoke plume. The strong initial mixing that takes place and the slight buoyancy of the smoke near the source leads to some uncertainty in the value of this parameter, although the effect of this uncertainty is expected to be quite small.

4.1.2 HOTMAC/RAPTAD

The HOTMAC/RAPTAD model was run for only two of the seven stable releases, due to the fact that this work had to be (due to the high cost of purchasing the code) contracted out to the model developer (Dr. Yamada). The option of running the HOTMAC/RAPTAD code ourselves was preferred, but the cost (approximately $43K) was prohibitive for this validation study. Since all seven stable smoke releases were very similar to each other, it was believed that any two tests would sufficiently represent the data. Trials 0930871 and 1001871 were chosen to compare with HOTMAC/RAPTAD since the data for these tests were complete (i.e. Transects No. 6 data were taken). In order to provide for an objective comparison of the HOTMAC/RAPTAD model with the data, all data except the actual measured fog-oil smoke concentration information were provided to Dr. Yamada. Four critical types of input were required by, and provided to, the developer to run the HOTMAC/RAPTAD models: (1) terrain data; (2) vegetation data; (3) meteorological data; and (4) source data.

Both terrain and vegetation information were provided in detail for a 5-km by 5-km area in the vicinity of the stable release point, with elevations/heights provided every 100 m in both the North-South and East-West directions. All of the available meteorological information from the AMADEUS study was provided to Dr. Yamada, as presented in a companion report (Brown, 1990). Based on the information provided in

Brown's report, Dr. Yamada made the following assumptions in order to initialize HOTMAC/RAPTAD model:

1) The meteorological input to the model was an initial wind profile at the SW corner of the computational domain. The wind speed profile was assumed to have a logarithmic variation from the ground up to the ambient wind speed of 3 m/s for Trial 0930871 and 3.3 m/s for Trial 1001871.

2) Initial wind profiles at other locations were obtained by correcting the winds at the SW corner based on the elevation of the terrain.

3) Wind directions were initially assumed to be 130 degrees for Trial 0930871 and 127 degrees for Trial 100171.

4) The vertical profile of potential temperature was estimated from the information in Brown's report. These profiles were assumed to be uniform in the horizontal directions.

Source release rate data was provided to the model as a release rate averaged over the duration of the trial. As with the WADOCT model, the release height was chosen to be 3 m above the ground for input into HOTMAC/RAPTAD.

4.1.3 RAMS

The most up-to-date version of RAMS computer code (current as of the date of this report) was obtained through ASTeR, Inc., and input files were prepared in consultation with the developers. An attempt was made to run the RAMS model for Trial 0930871. Some of the important input data to the RAMS model include: (1) terrain data, (2) meteorological data, (3) source data, and (4) the configurations of the vertical and horizontal nested grids.

Terrain information was available in detail for a 5-km by 5-km area in the vicinity of the stable release point, with elevations provided every 100 m in both the North-South and East-West directions. Furthermore, terrain information was provided in less detail, every 500 m in both the North-South and East-West directions over a larger area about the stable release point. In Trial 0930871, as with all of the stable releases, the ground-level winds were dominated by downslope drainage flow from the east, opposing westerly synoptic winds occurring at higher altitudes. These meteorological data, as well as soil temperature data, provided the initial conditions for the model. Test duration and average release rates were also provided for the model runs.

RAMS makes its predictions on a three-dimensional grid of points. This requires an input of both a horizontal 'nested' grid and a vertical grid. With finer grid spacing, the model can better predict the small-scale phenomena, but at the cost of more CPU time. Furthermore, given the size of our domain of interest (within 3-km from the stable release point), a large area (40 km x 20 km) must be simulated in order to provide the appropriate boundary conditions for our domain of interest. Therefore, a compromise was required in order to keep the number of grid points to a reasonable level and still have the computational domain cover the area suggested by the developers. Since the horizontal grid could be nested (i.e. different grid spacing in different domains), the grid spacing near the source (where we are most interested) was set at 25 m and at distances further away from the source the grid spacing was on the order of 1/2 km.

The user's manual for the RAMS model suggests that vertically nested grids are possible, but this was not an option in the version of RAMS received for use in this study. Grid spacing was not allowed to be nested in the vertical, as such a constant value was required. Since the Meadowbrook area is quite hilly, with numerous steep-walled valleys, RAMS was not capable of running successfully with a vertical grid spacing of less than 60 meters, even with significant terrain smoothing. The underlying numerical integration algorithm severely constrains the vertical resolution that is possible to achieve. To ensure stability, the spacing between vertical grid layers must be on the order of the difference in ground elevation between any two adjacent horizontal grid locations. Therefore a vertical grid spacing of 60 meters was used in the model.

4.2 Results of Model/Data Comparisons

4.2.1 Overview of Model/Data Comparisons

The comparisons between model predictions and the data take four forms in this report. The first type of comparison is graphical in nature and shows the predicted wind field along with the observed winds at the meteorological towers (see Figures 4.1 - 4.10). Figures 4.1 - 4.7 show the wind fields for Trials 0925871, 0927871, 0927872, 0930871, 1001871, 1002871 and 1003871, as predicted by the WADOCT model. Figures 4.8 - 4.9 show the wind fields for Trials 0930871 and 1001871, as predicted by the HOTMAC model. Figure 4.10 shows the wind field for Trial 0930871, as predicted

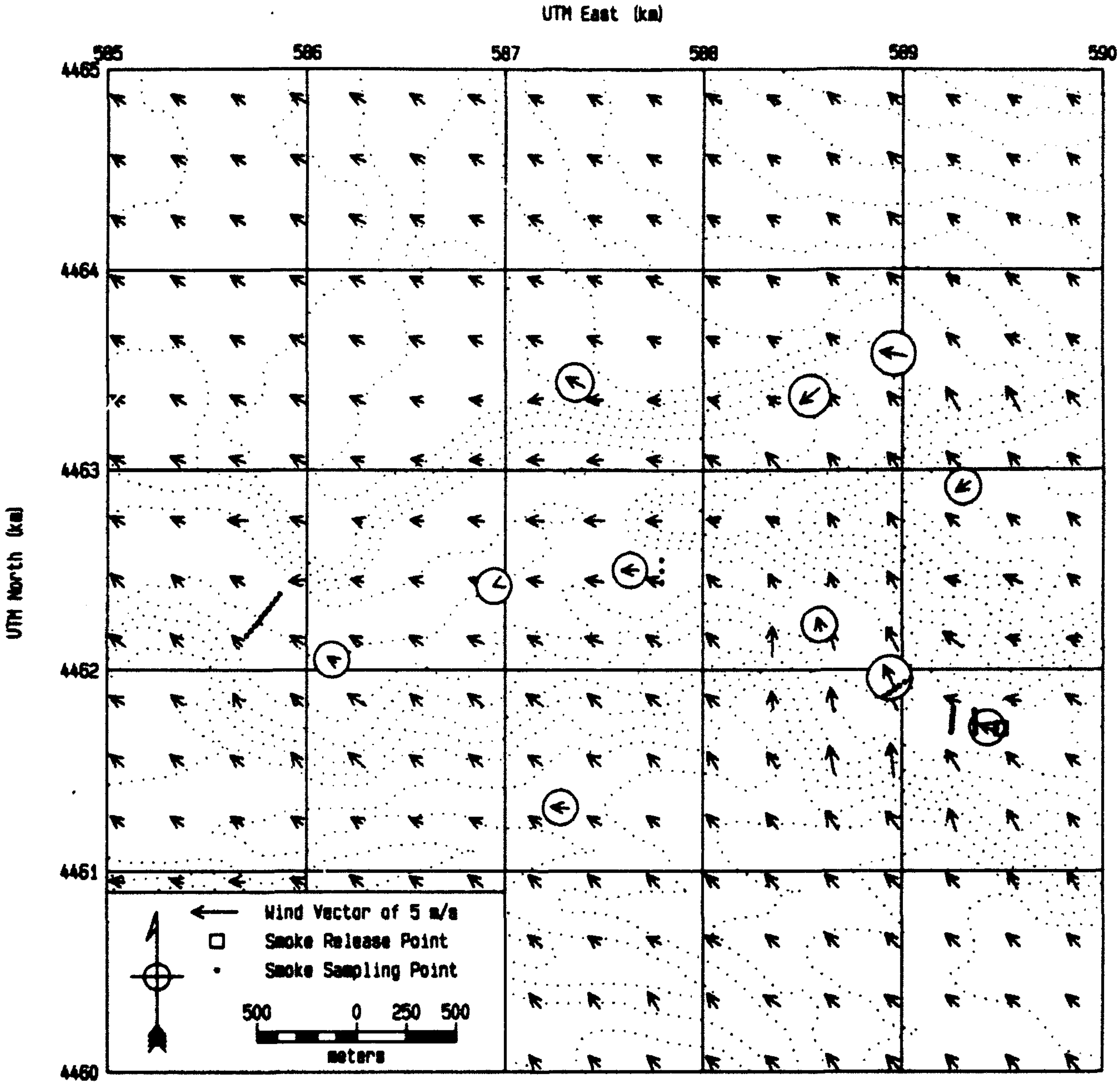


Figure 4.1 Computed Wind Field and Observed Wind Field for Trial 0925871 - WADOCT (observed winds are in circles).

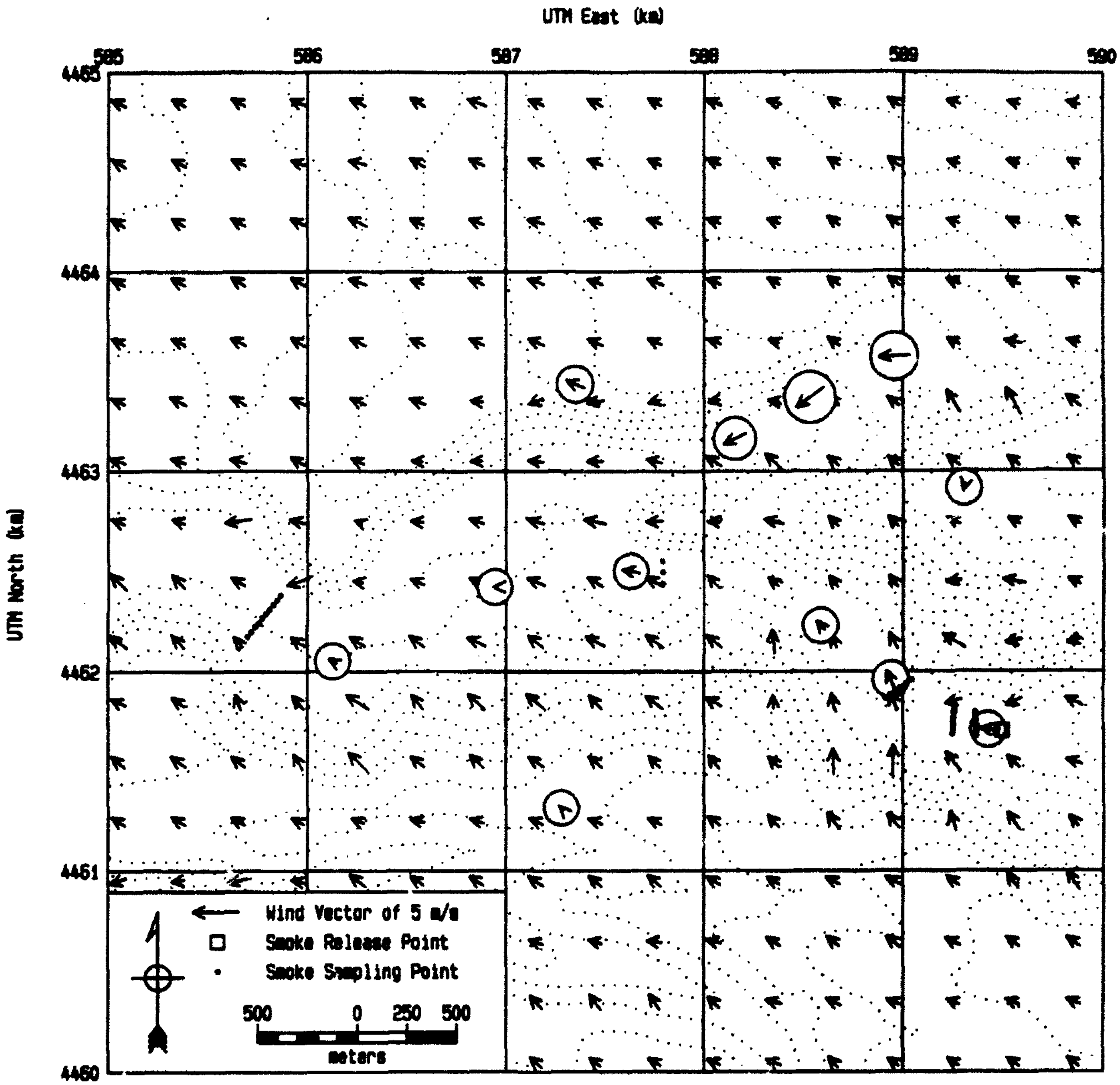


Figure 4.2 Computed Wind Field and Observed Wind Field for Trial 0927871 - WADOCT (observed winds are in circles).

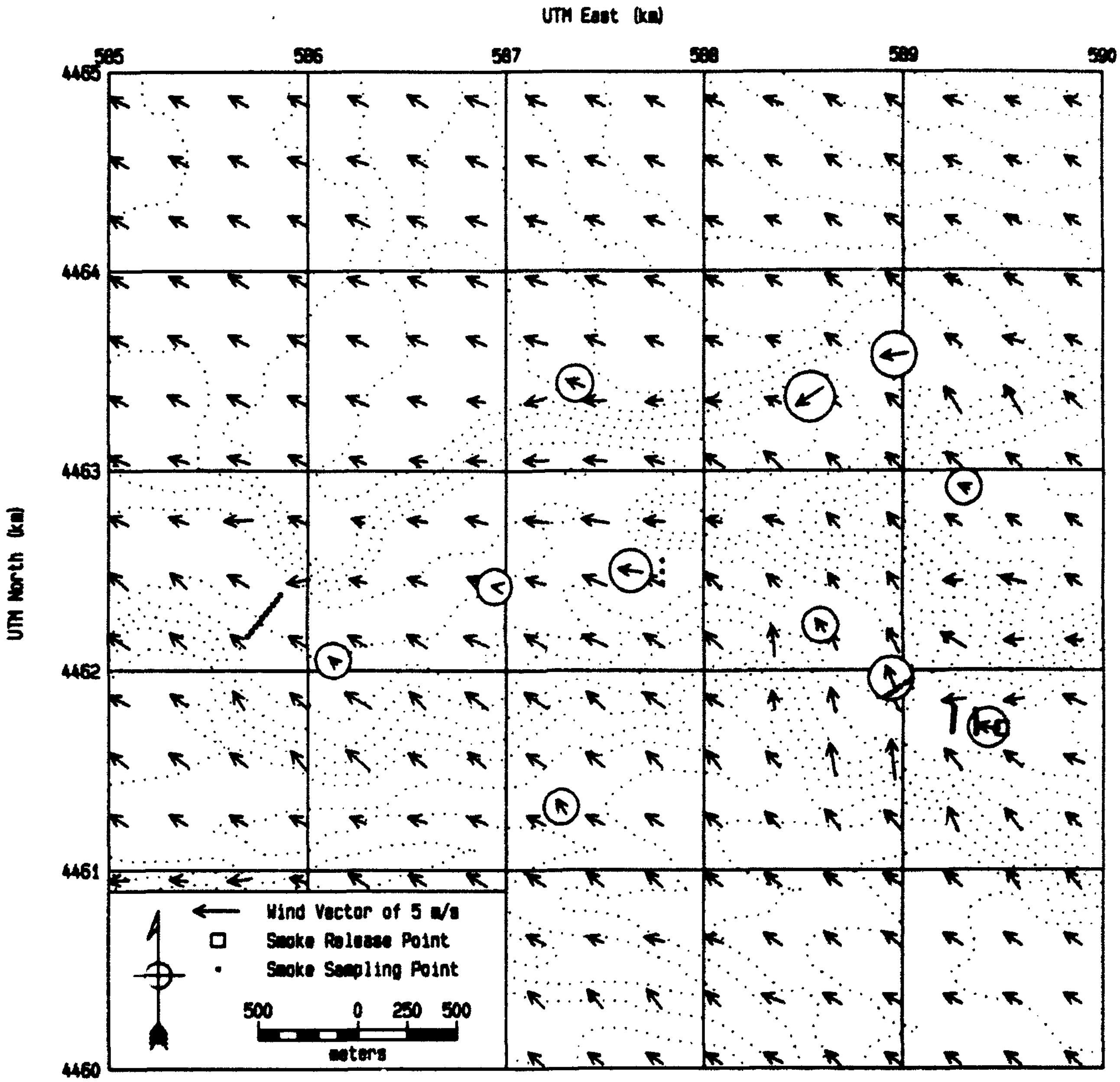


Figure 4.3 Computed Wind Field and Observed Wind Field for Trial 0927872 - WADOCT (observed winds are in circles).

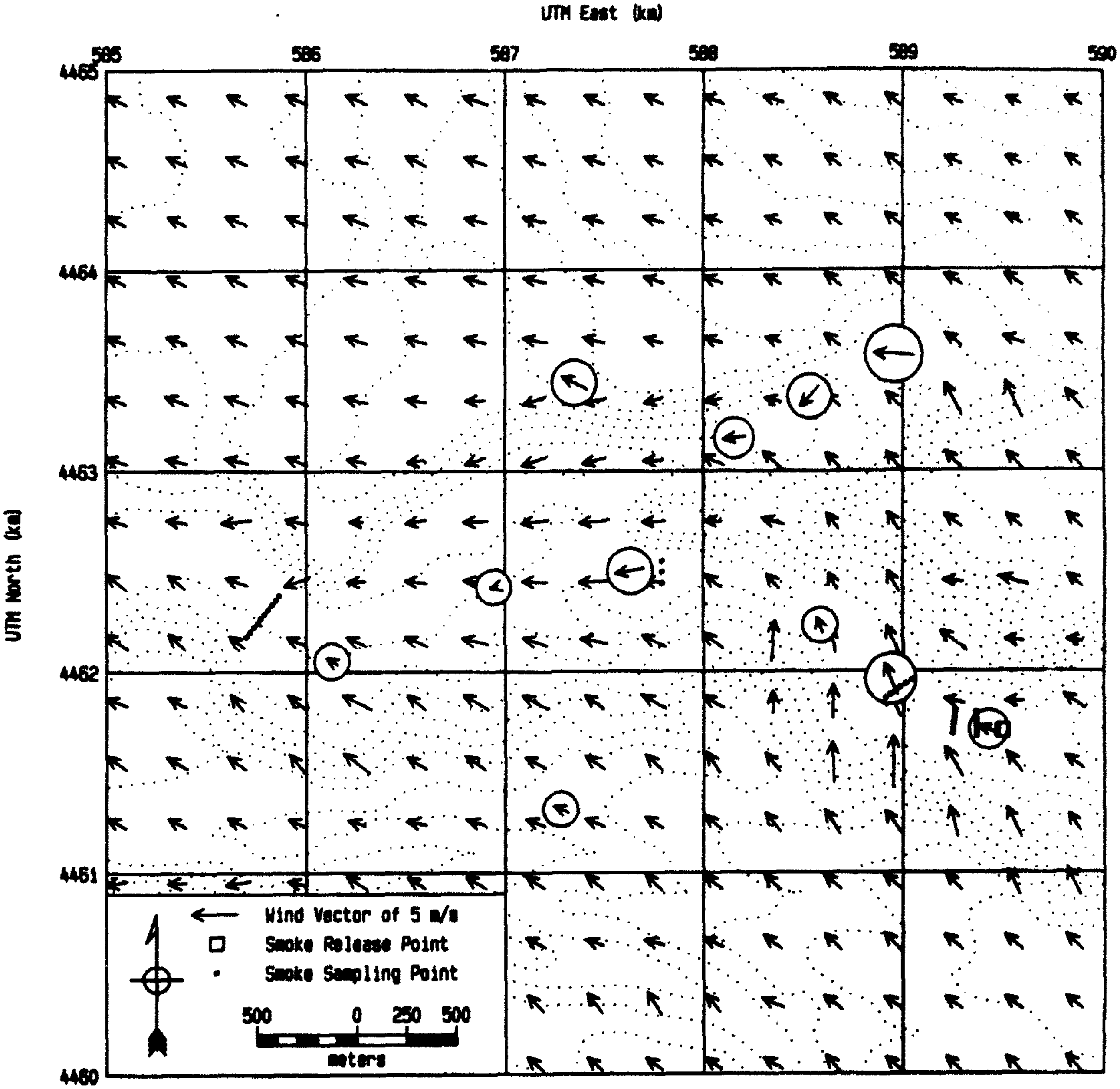


Figure 4.4 Computed Wind Field and Observed Wind Field for Trial 0930871 - WADOCT (observed winds are in circles).

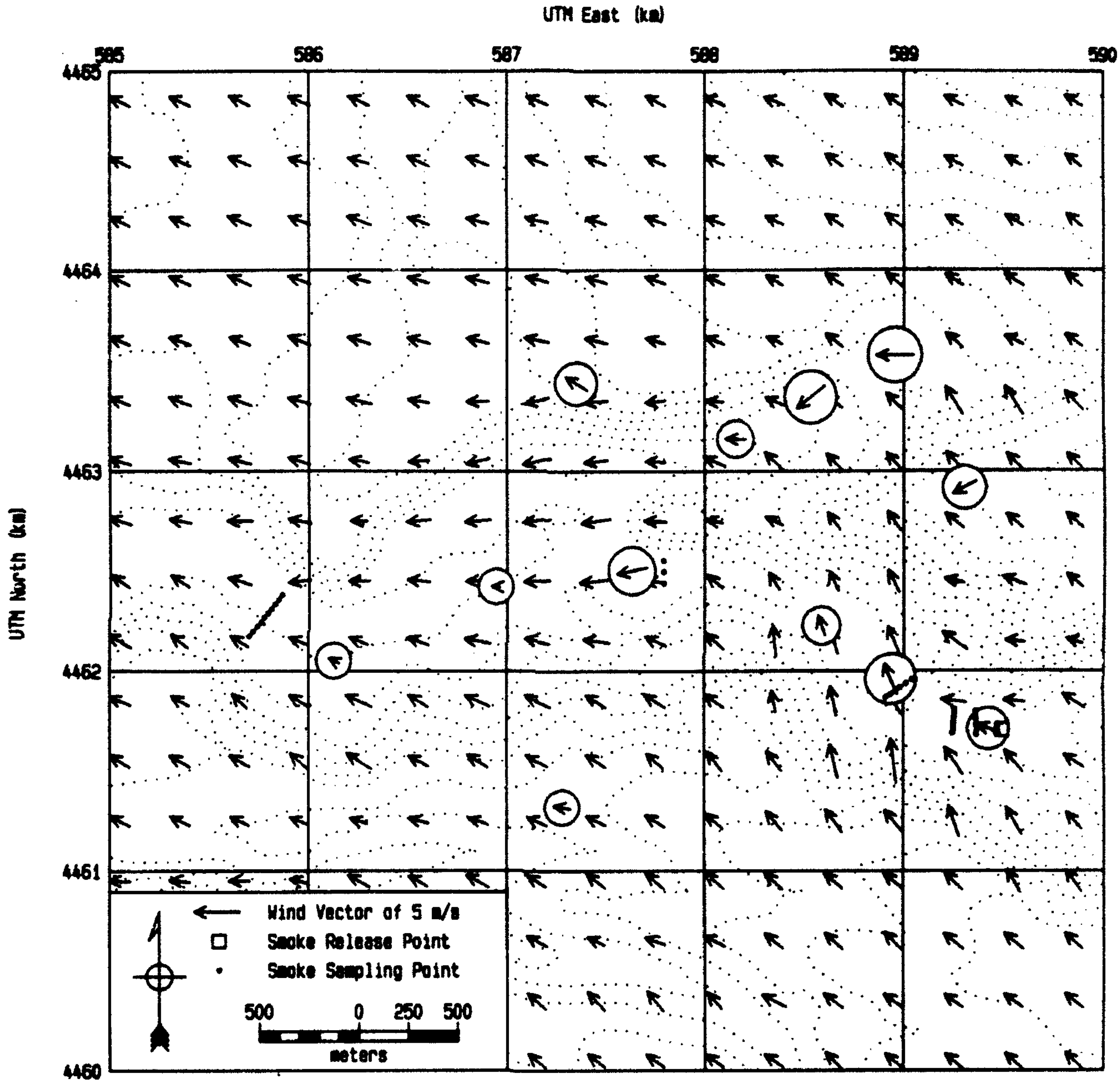


Figure 4.5 Computed Wind Field and Observed Wind Field for Trial 1001871 - WADOCT (observed winds are in circles).

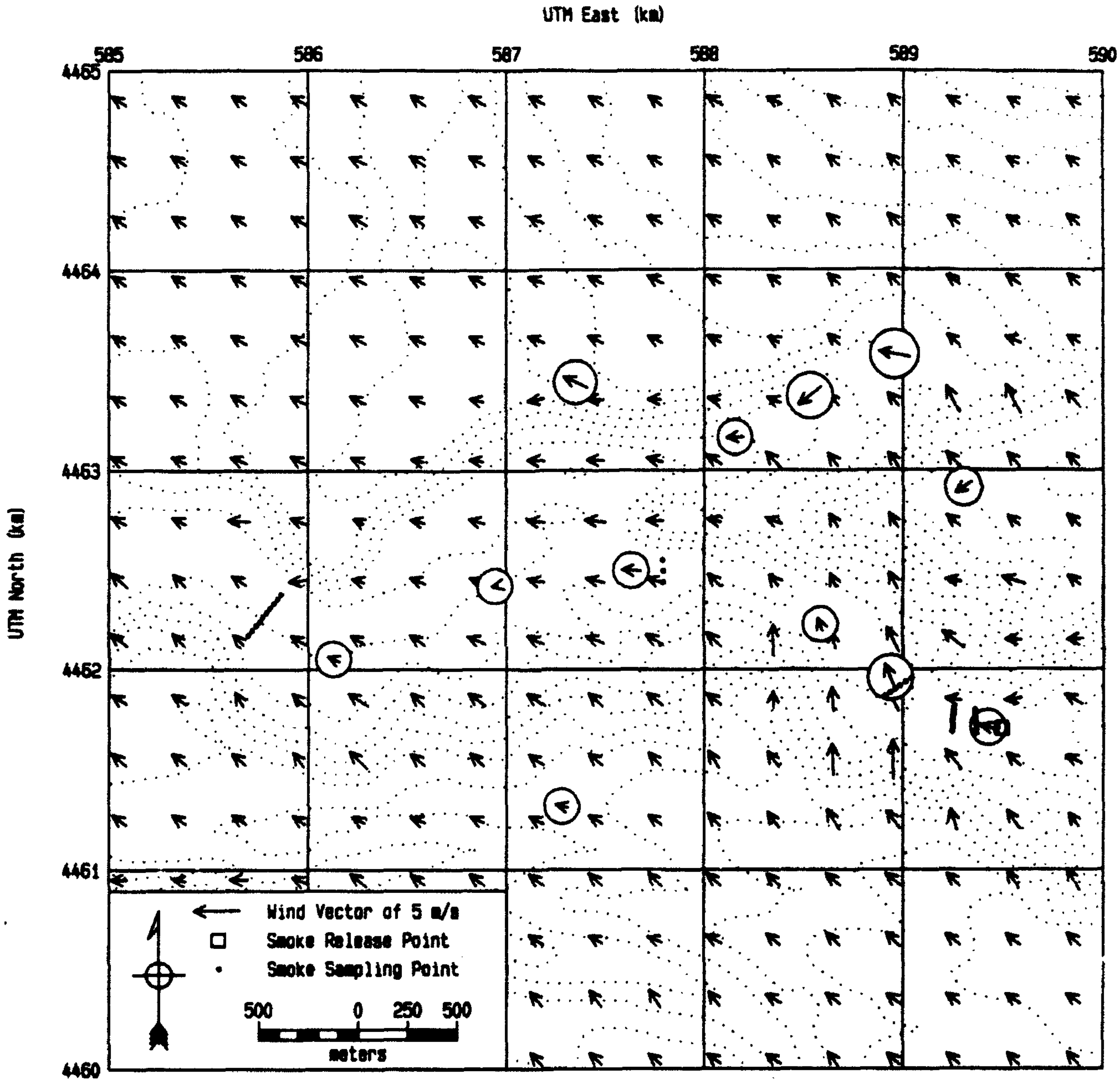


Figure 4.6 Computed Wind Field and Observed Wind Field for Trial 1002871 - WADOCT (observed winds are in circles).

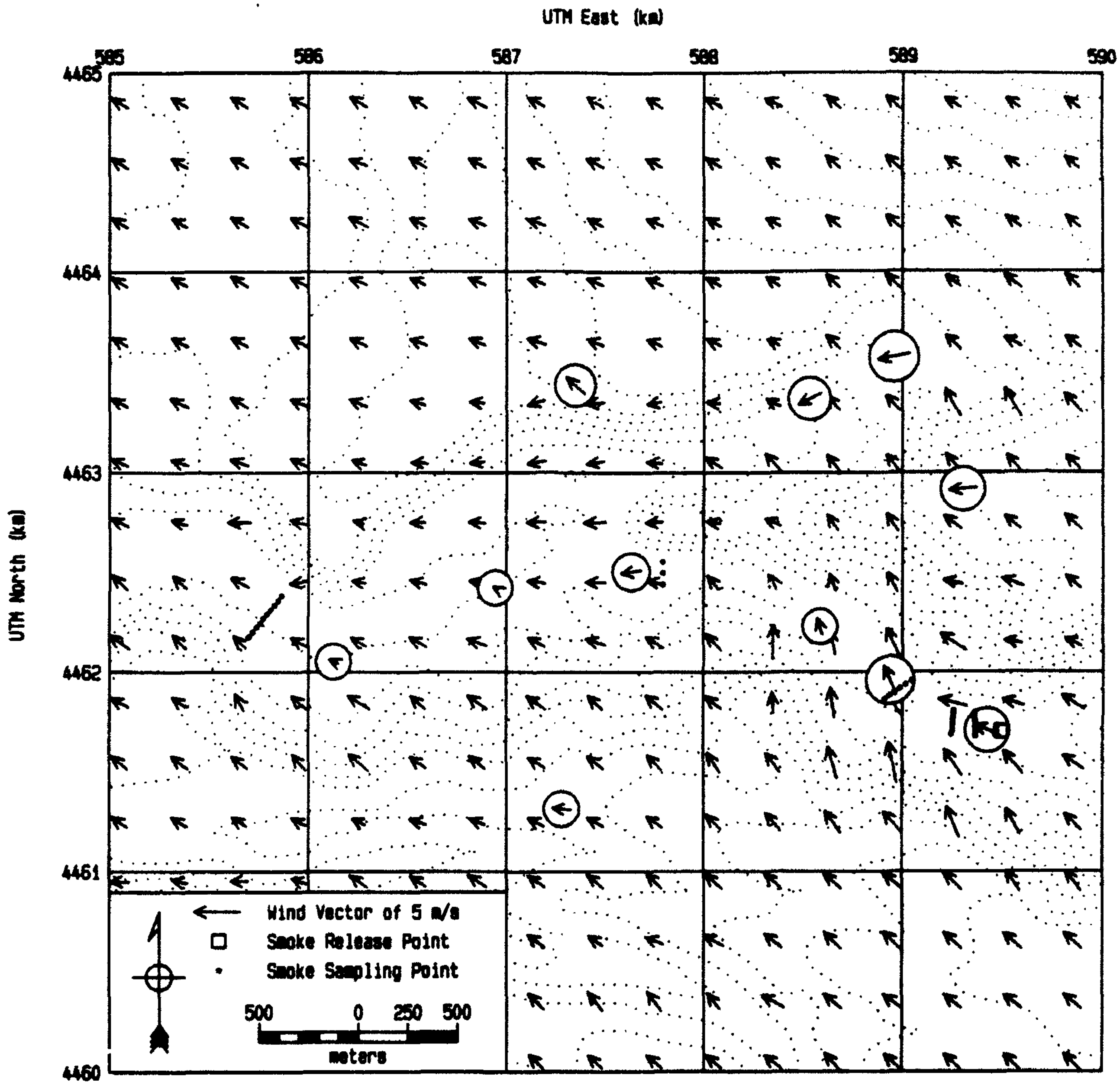


Figure 4.7 Computed Wind Field and Observed Wind Field for Trial 1003871 - WADOCT (observed winds are in circles).

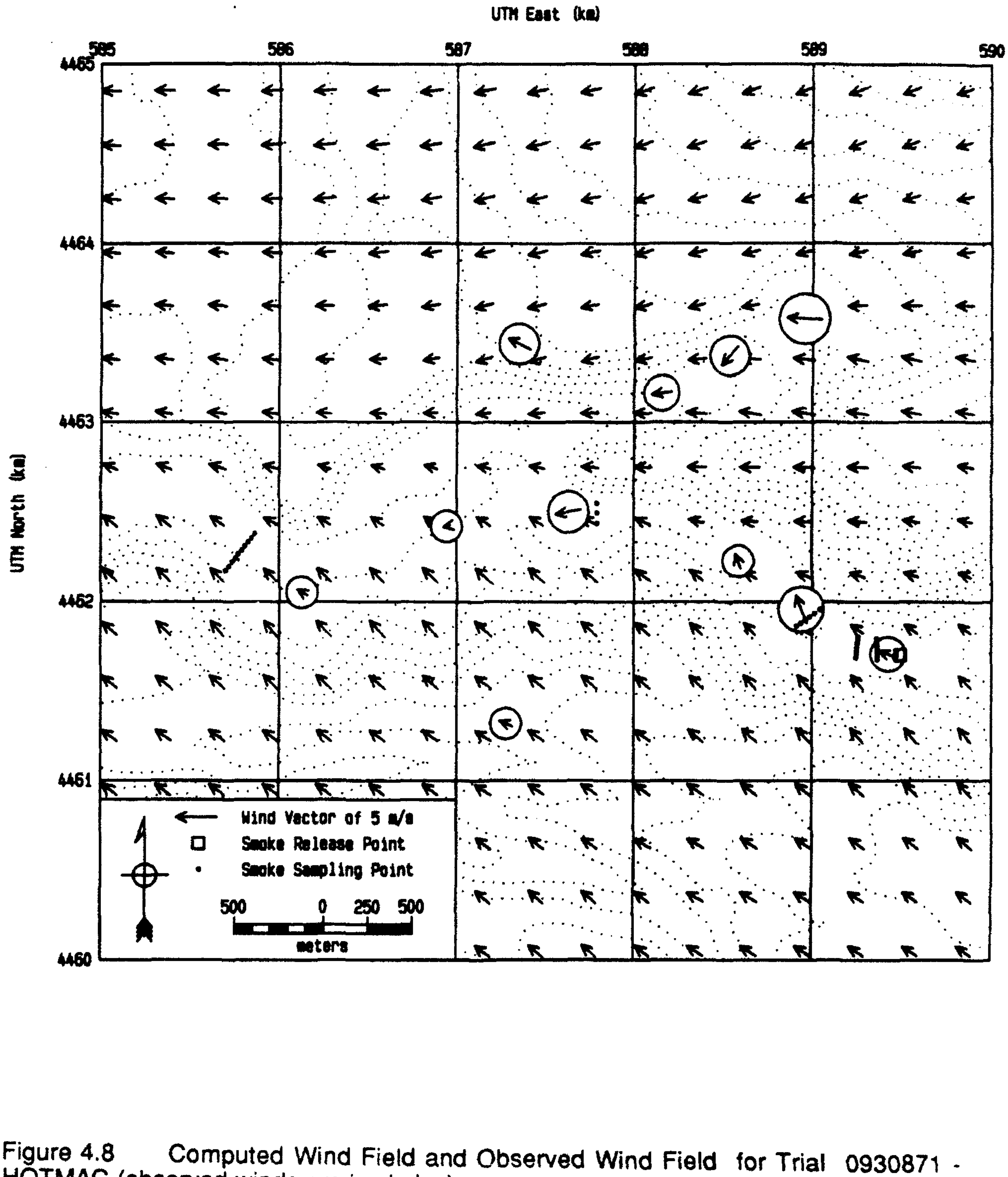


Figure 4.8 Computed Wind Field and Observed Wind Field for Trial 0930871 - HOTMAC (observed winds are in circles).

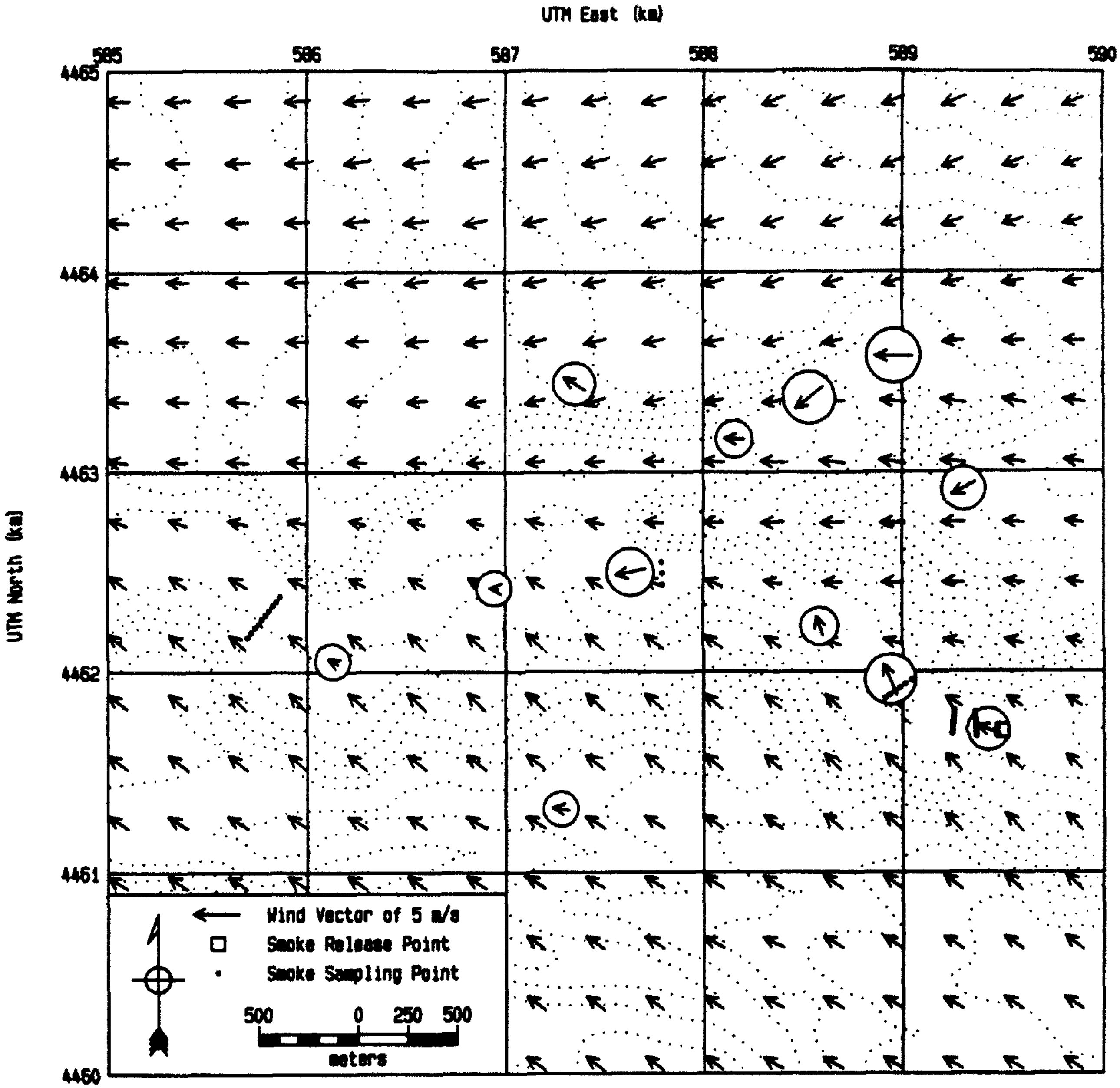


Figure 4.9 Computed Wind Field and Observed Wind Field for Trial 1001871 - HOTMAC (observed winds are in circles).

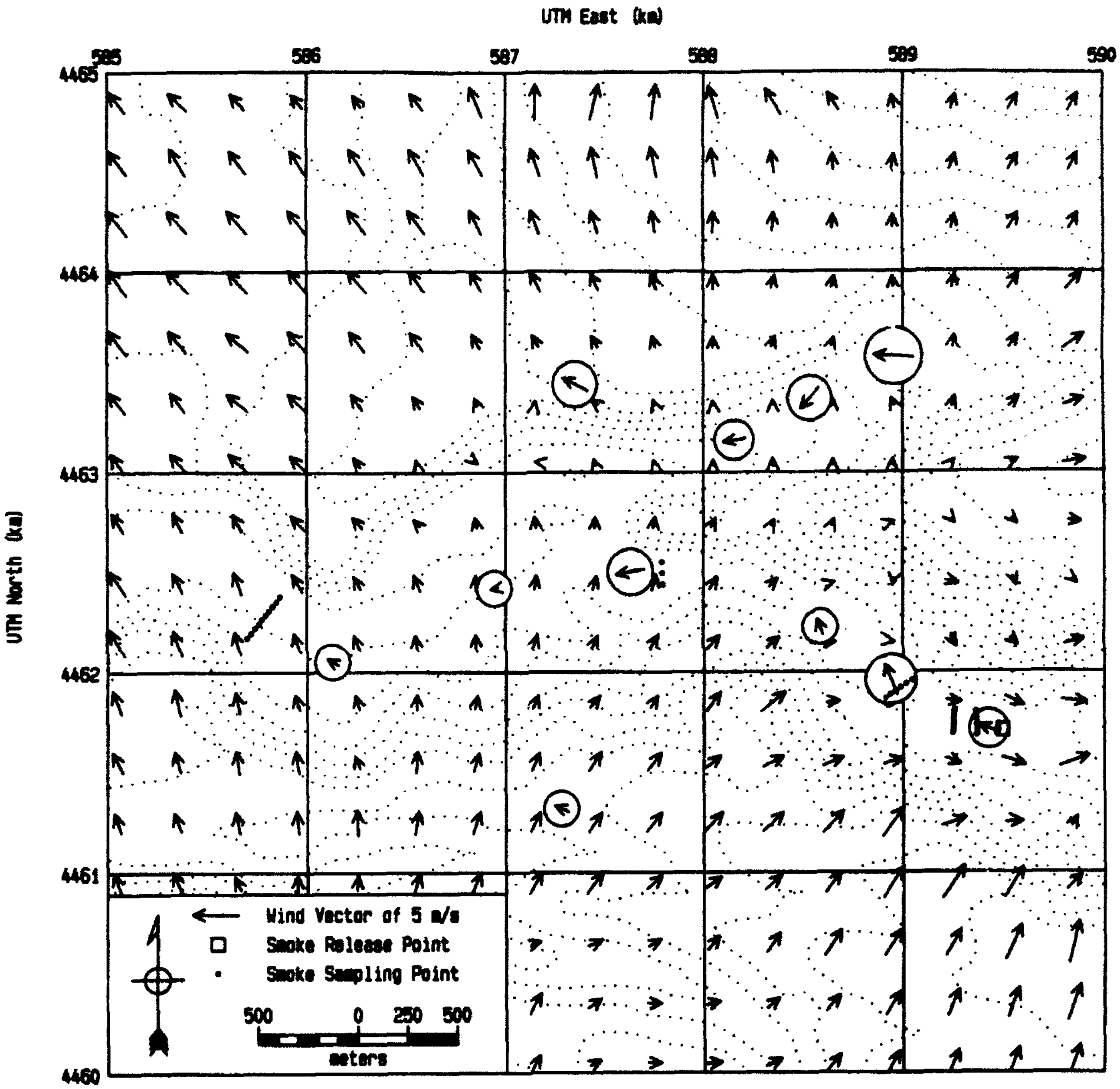


Figure 4.10 Computed Wind Field and Observed Wind Field for Trial 0930871 - RAMS (observed winds are in circles).

by the RAMS model. This comparison among wind field models is important, in that it demonstrates whether or not the primary mechanism for the dispersion of the fog-oil is correctly predicted.

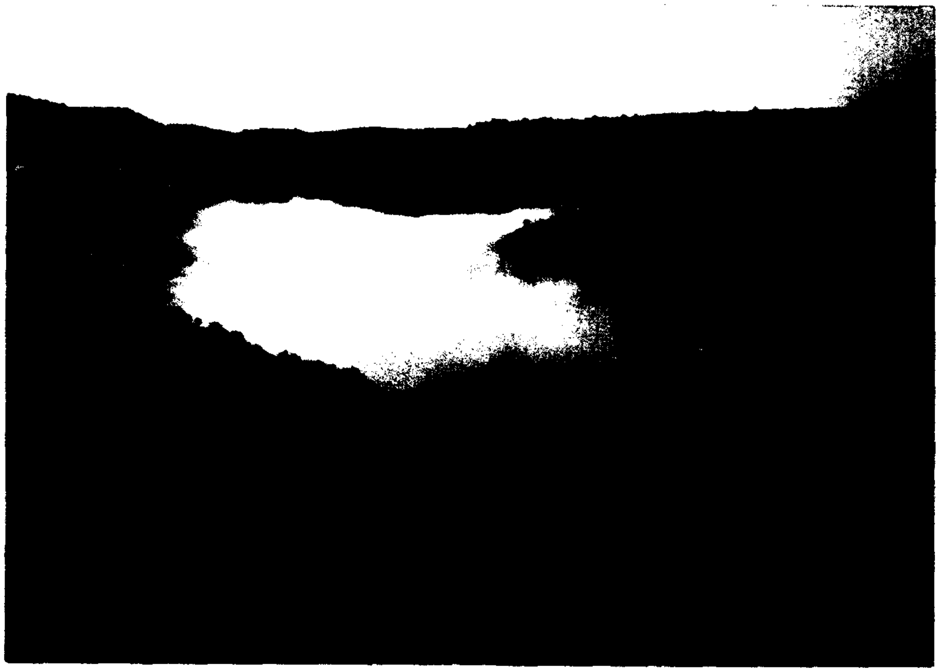
The remaining comparisons are concerned with the average concentrations due to the dispersion of the fog-oil. The measured fog-oil concentrations are presented in Appendix A. Figure 4.11 is a seset of two photographs taken during Trial 0930871, which helps the reader to visualize fog-oil dispersion in the valley.

The second type of comparison is a graphical representation comparing model predictions with data on a transect-by-transect basis. This is the most natural method of presentation for the concentrations, and provides valuable insight into the models' ability to correctly predict the trajectory and spreading of the plume as well as the magnitude of the maximum concentration at each transect. Figures 4.12 – 4.17 present these comparisons for Trials 0925871, 0927871 (combined with the results of Trial 0927872), 0930871, 1001871, 1002871 and 1003871, respectively.

Both the model predictions and the data presented in Figures 4.12 – 4.17 represent an average of the 2-m and 8-m values. Since the data differ between both the 2-m and 8-m predictions on Transects 1-4, Figure 4.18 separately compares the 2-m and 8-m model/data predictions for Trials 0930871.

The third type of comparison is also graphical and presents concentration contours as predicted by each of the various models. Predicted concentration contours are presented in Figures 4.19 - 4.25 for Trials 0925871, 0927871, 0927872, 0930871, 1001871, 1002871, and 1003871 (as predicted by the WADOCT model); Figures 4.26 and 4.27 for Trials 0930871 and 1001871 (as predicted by the RAPTAD model); and Figure 4.28 for Trial 0930871 (as predicted by the RAMS model).

The fourth type of comparison represents an attempt to better quantify the relative performance of the models. To this end, the number of predicted concentrations that fall within a given factor (e.g., factor of 2) of the data are tabulated. These results are presented on a trial-by-trial basis in Table 4.1. We have chosen to use factors of 2, 3, 4, 5 and 10 for the tabulation. Since the data are believed to be accurate to within a factor of 2, a model which is similarly accurate can be expected to predict within a factor of about 2.8 whether the differences are independent (correlation coefficient of



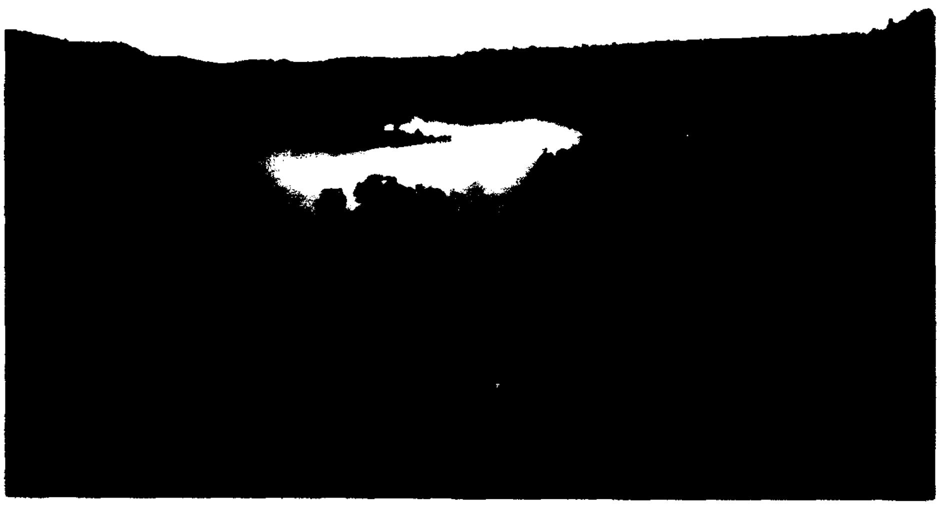


Figure 4.11 Photographs of Fog-Oil Plumes Dispersing into Paynes Creek Valley During Stable Releases.

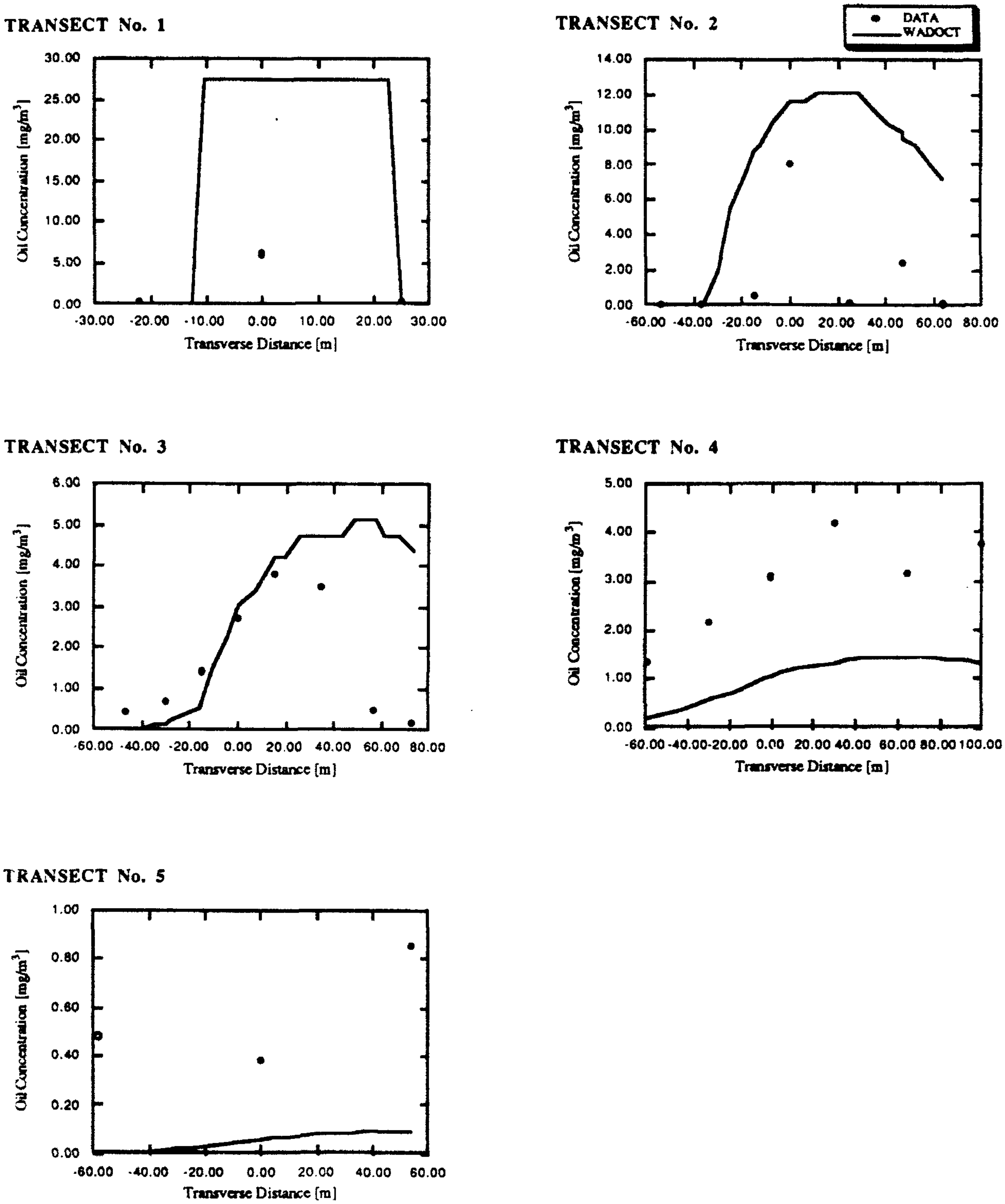


Figure 4.12 Comparison of the WADOCT Model Predictions with Average Concentration Data for Trial 0924871.

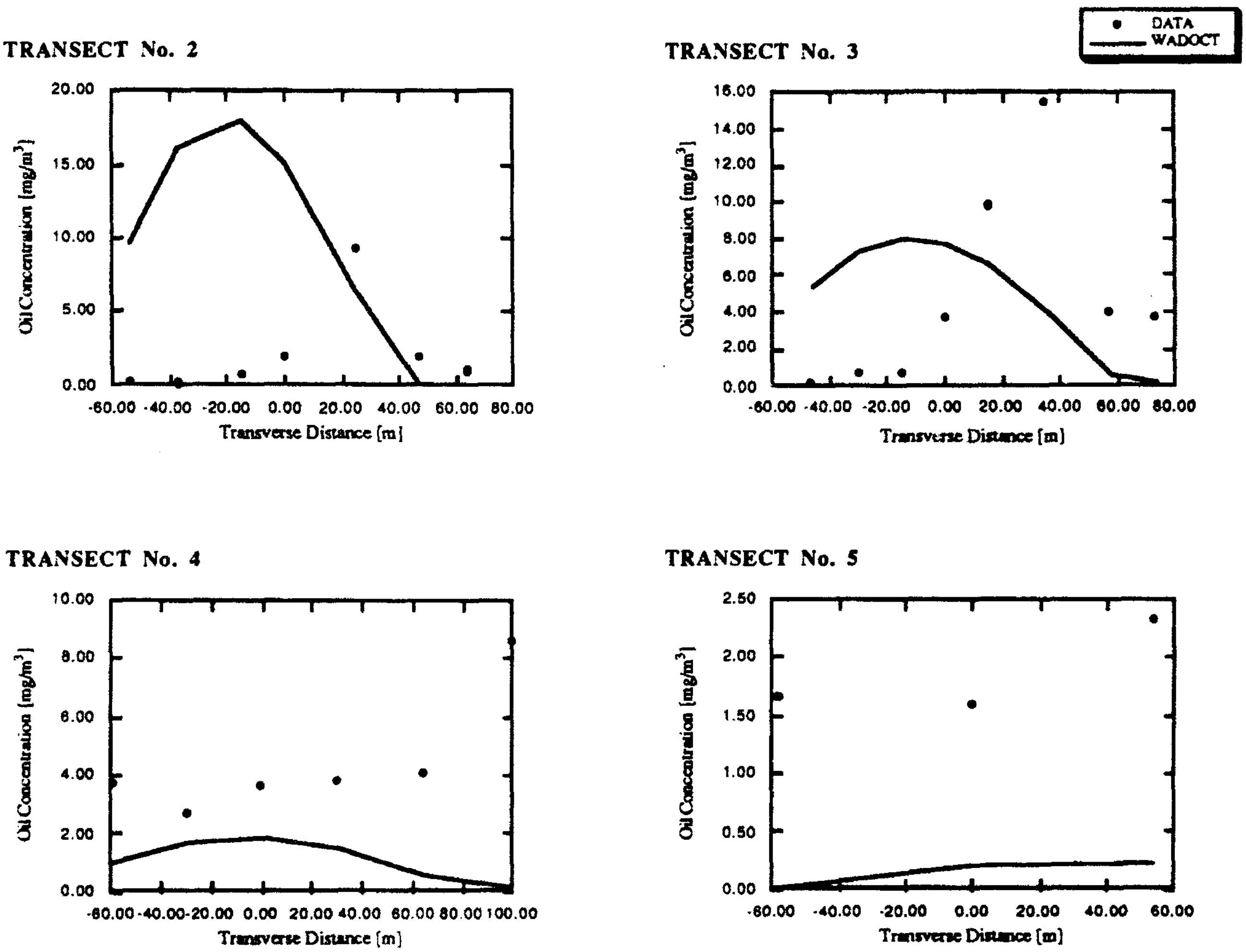


Figure 4.13 Comparison of the WADOCT Model Predictions with Average Concentration Data for Trials 0927871 and 0927872.

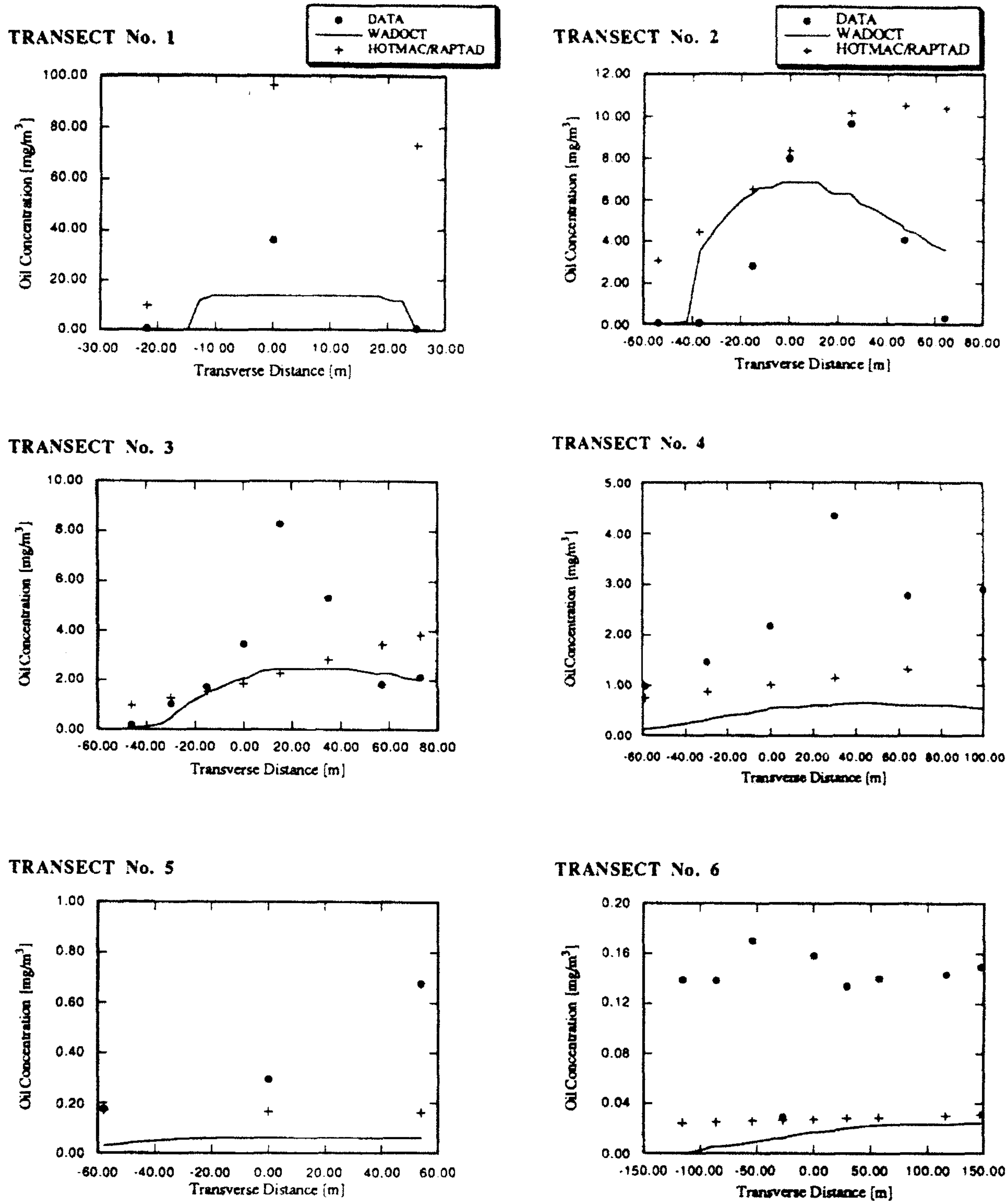


Figure 4.14 Comparison of the WADOCT and HOTMAC/RAPTAD Model Predictions with Average Concentration Data for Trial 0930871.

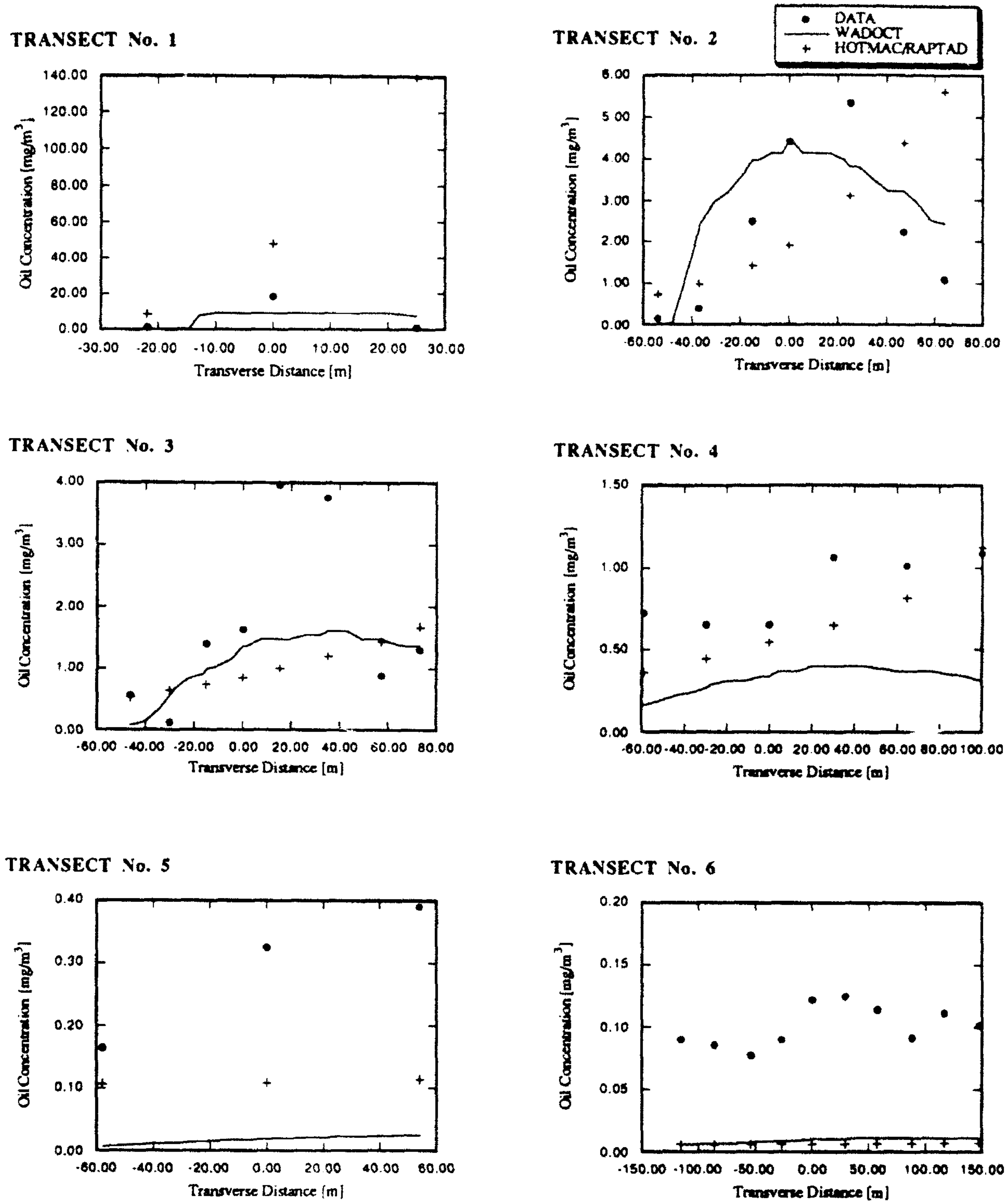


Figure 4.15 Comparison of the WADOCT and HOTMAC/RAPTAD Model Predictions with Average Concentration Data for Trial 1001871.

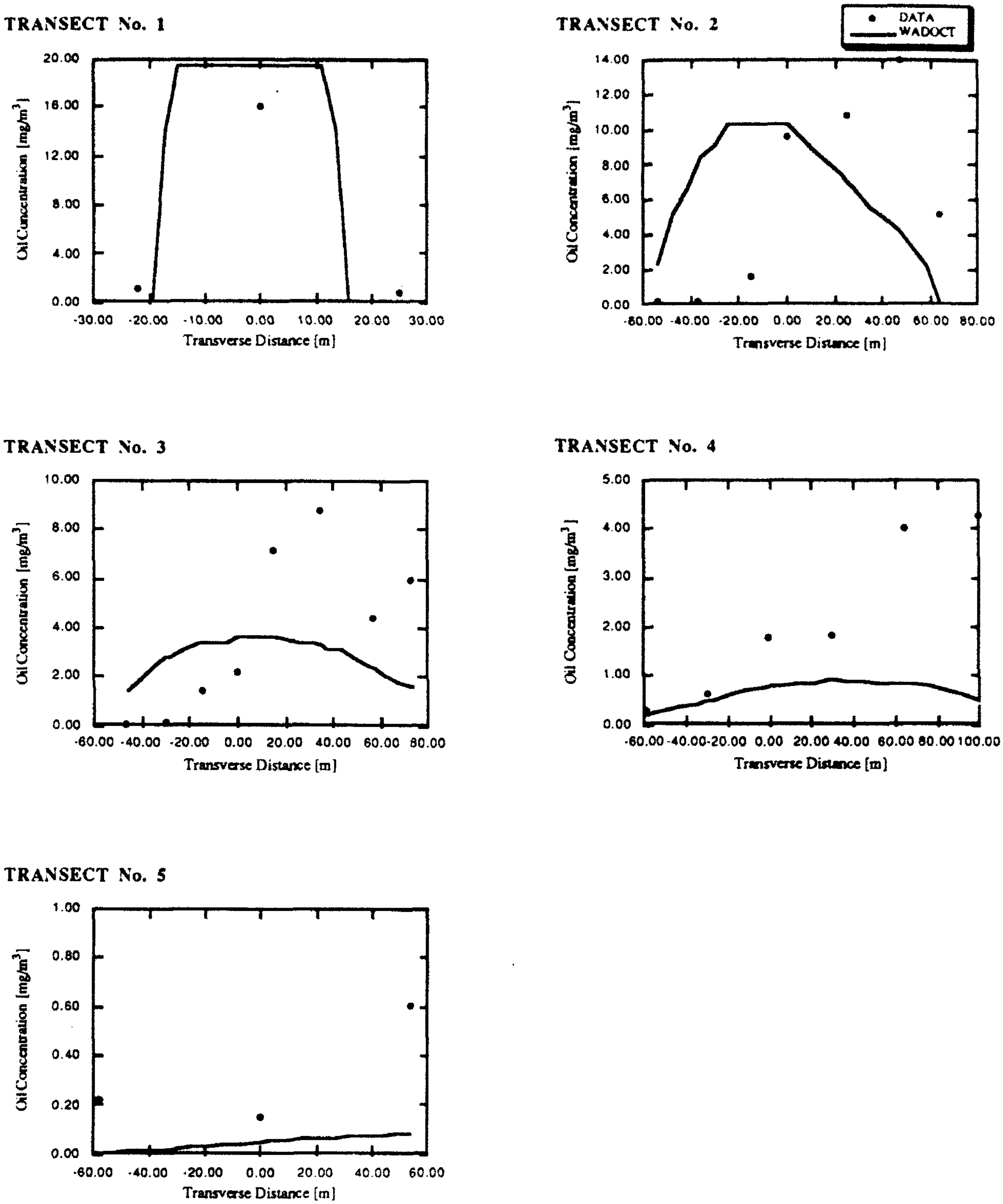


Figure 4.16 Comparison of the WADOCT Model Predictions with Average Concentration Data for Trial 1002871.

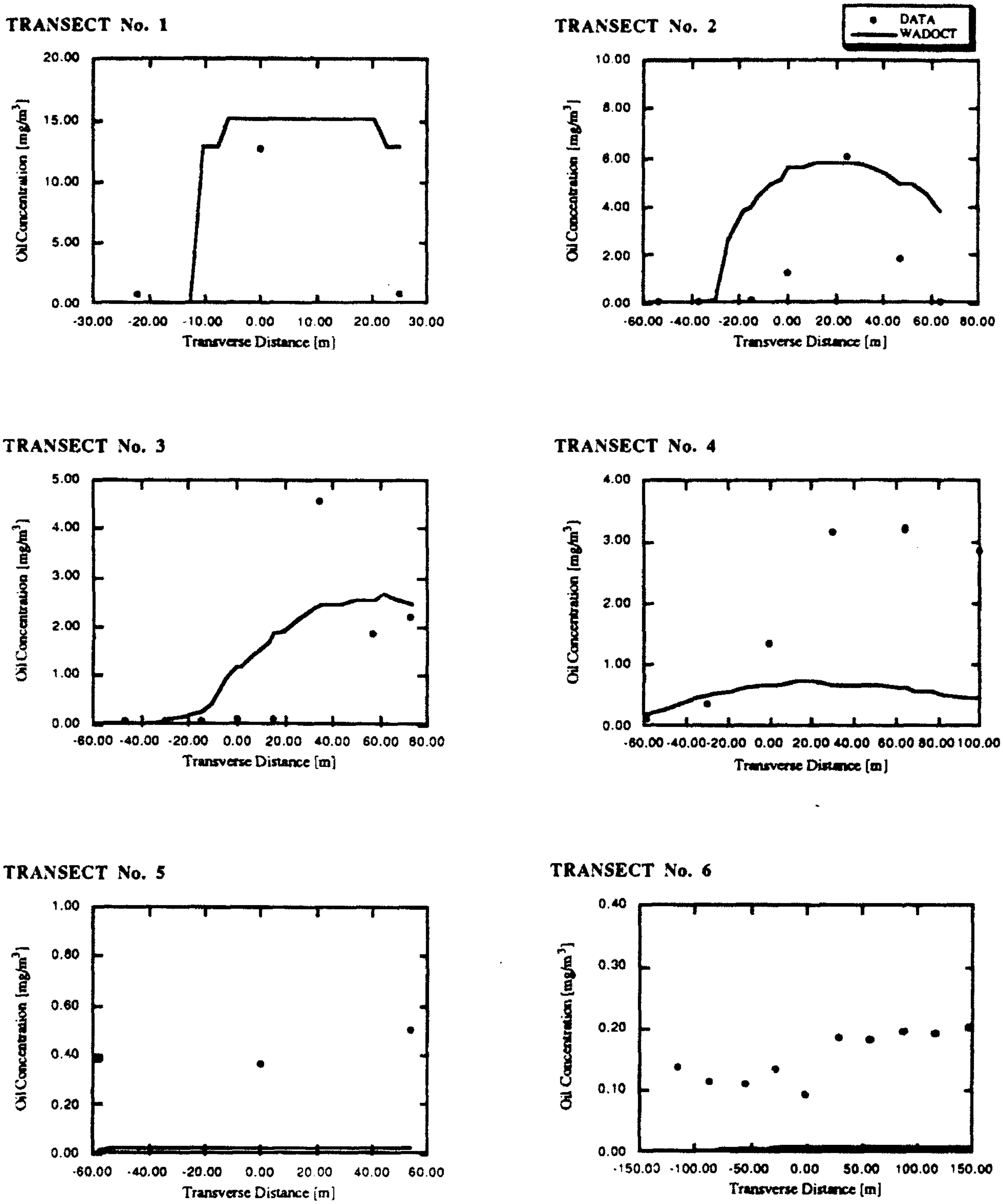


Figure 4.17 Comparison of the WADOCT Model Predictions with Average Concentration Data for Trial 1003871.

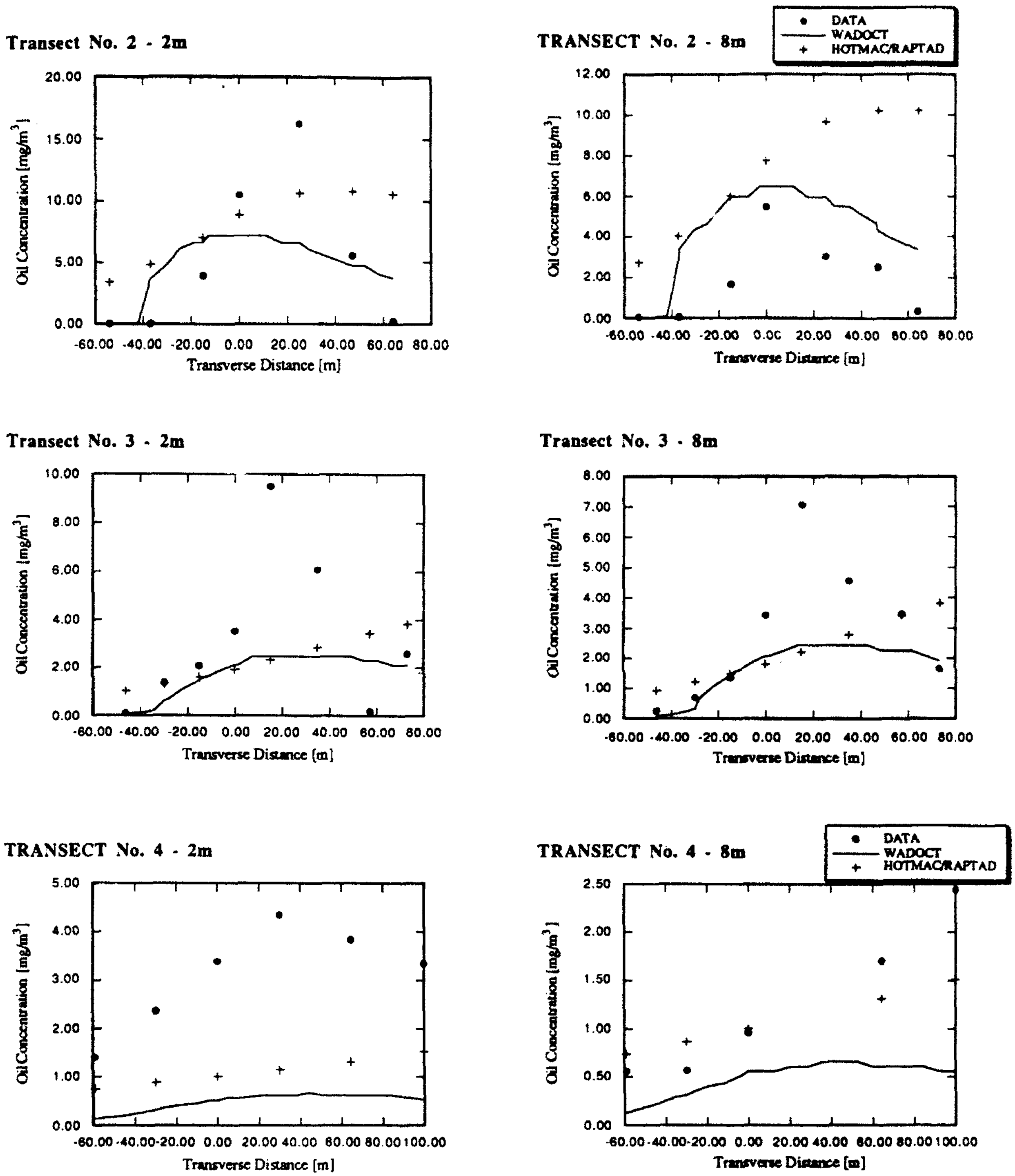


Figure 4.18 Comparison of the WADOCT and HOTMAC/RAPTAD Model Predictions with Average Concentration Data for Trial 0930871, at the 2m and 8m Levels.

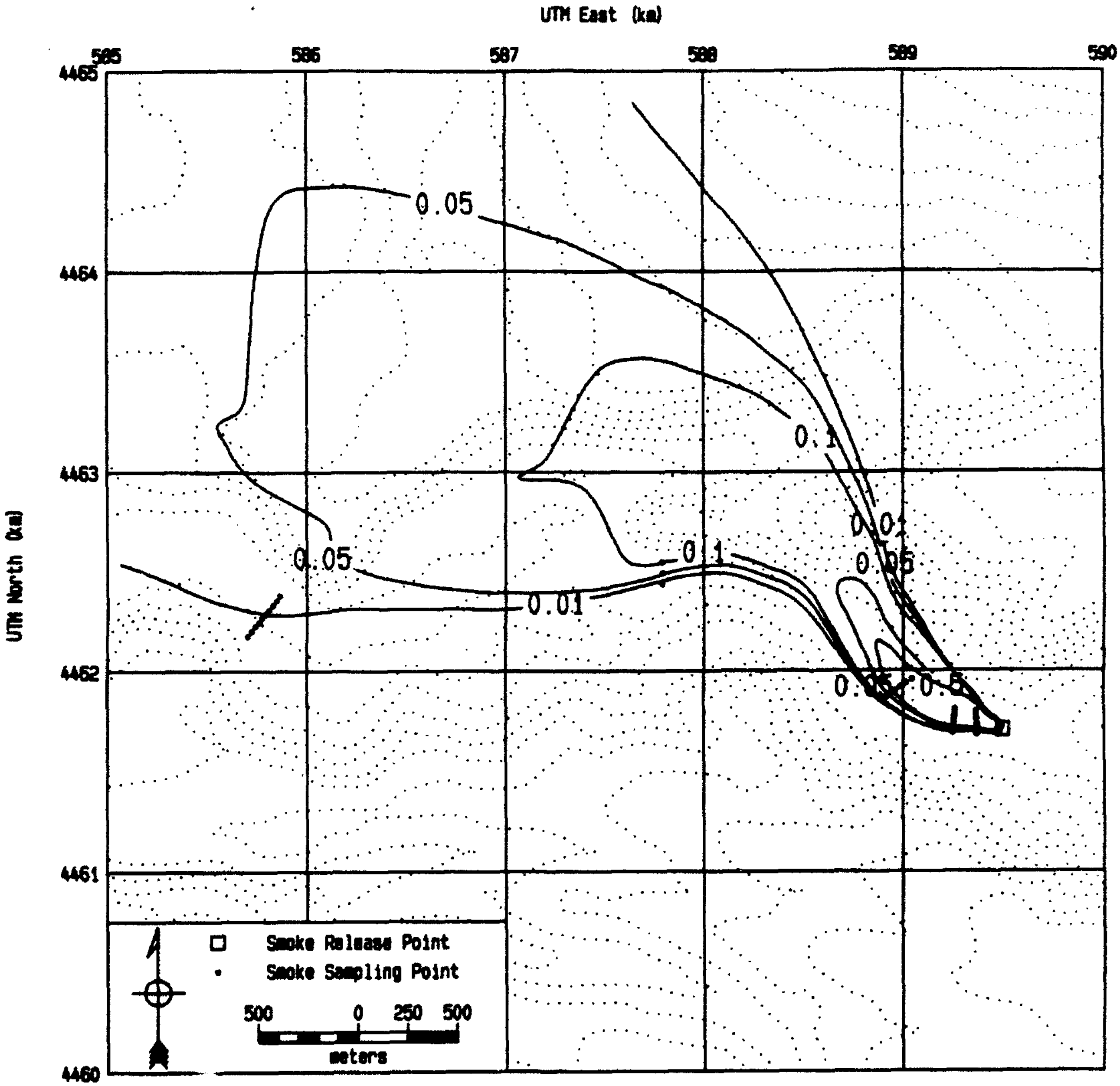


Figure 4.19 Computed Fog Oil Concentration Contours for Average Concentration for Trial 0925871 - WADOCT.

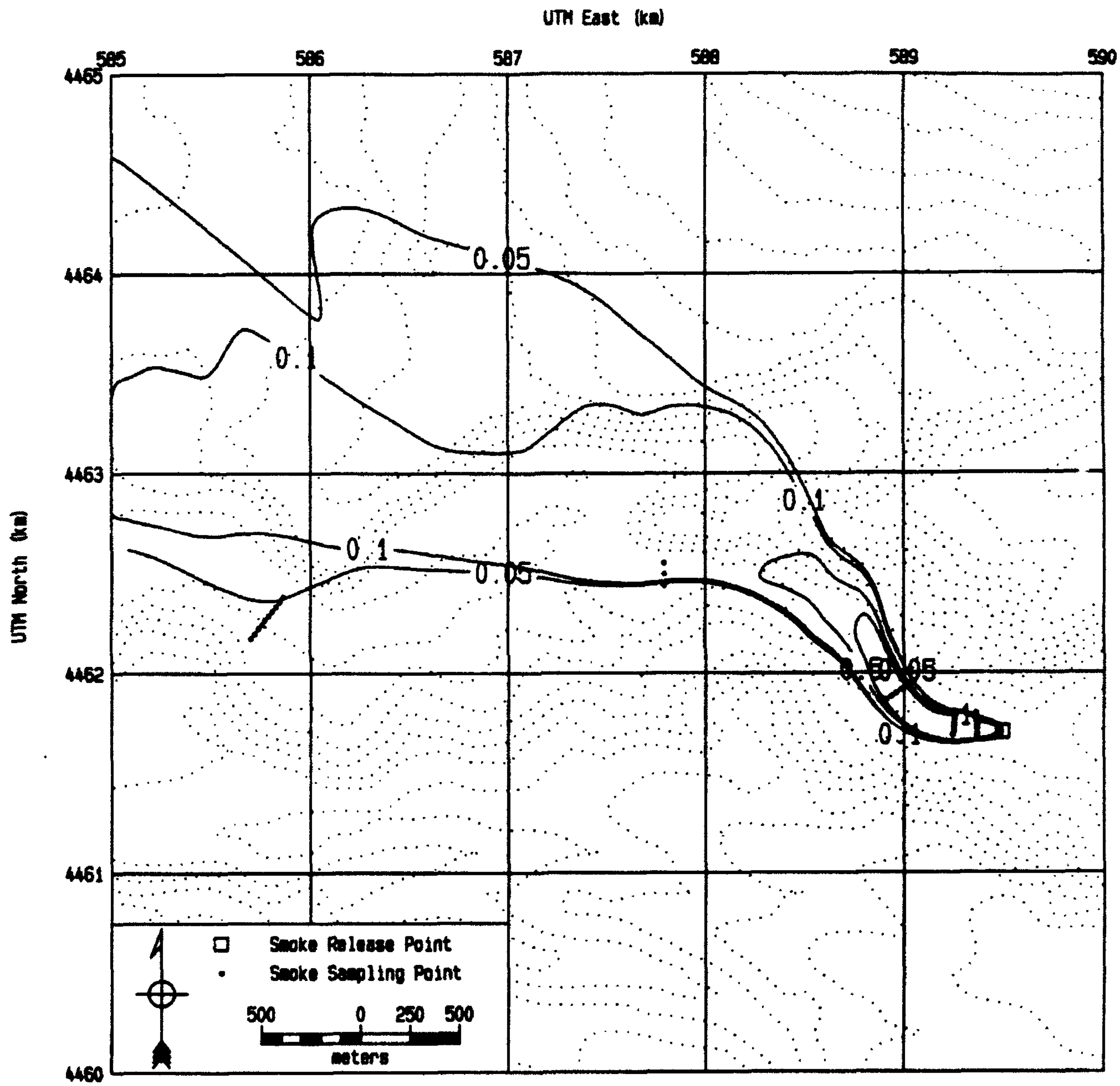


Figure 4.20 Computed Fog Oil Concentration Contours for Average Concentration for Trial 0927871 -WADOCT.

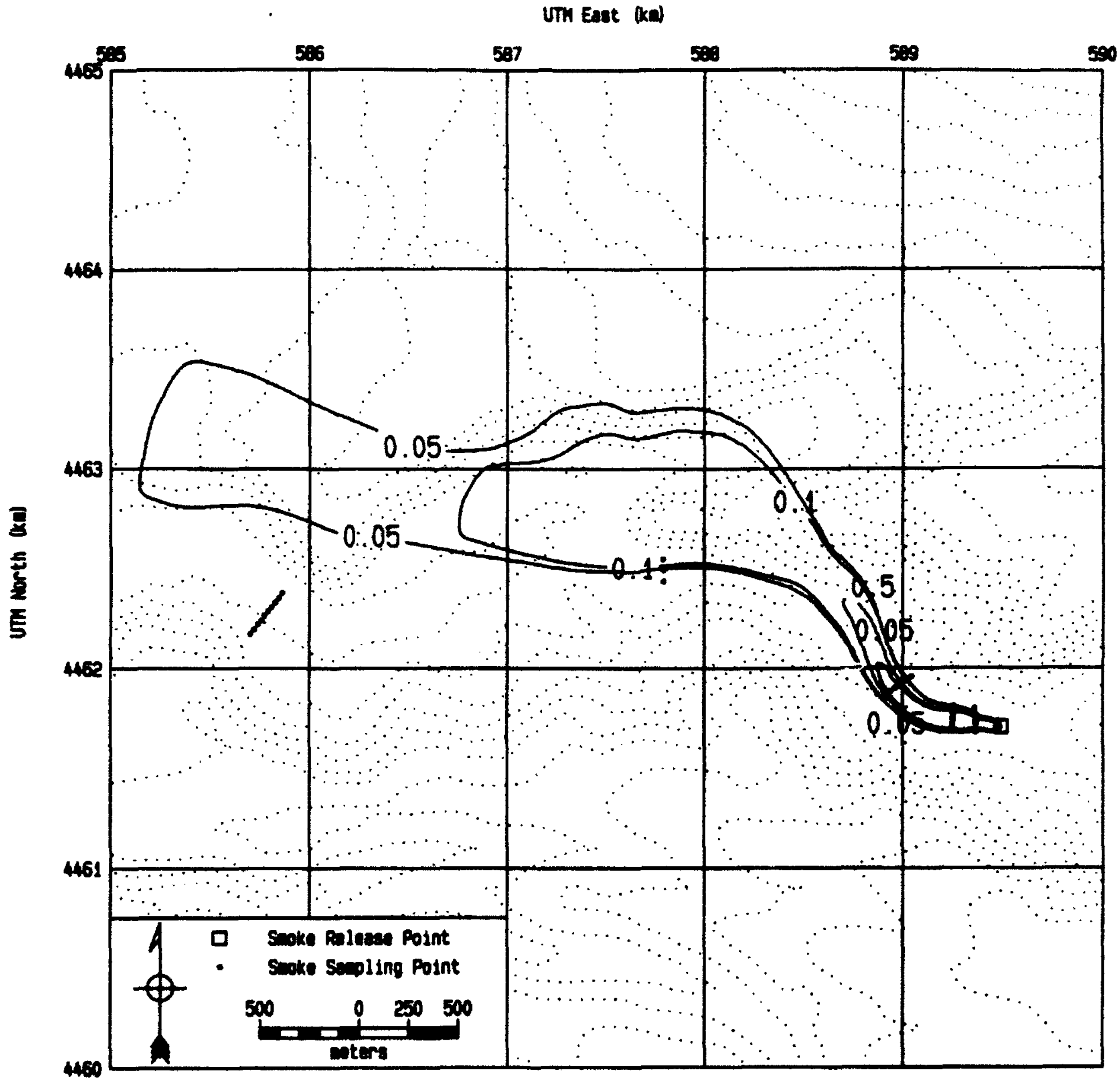


Figure 4.21 Computed Fog Oil Concentration Contours for Average Concentration for Trial 0927872 -WADOCT.

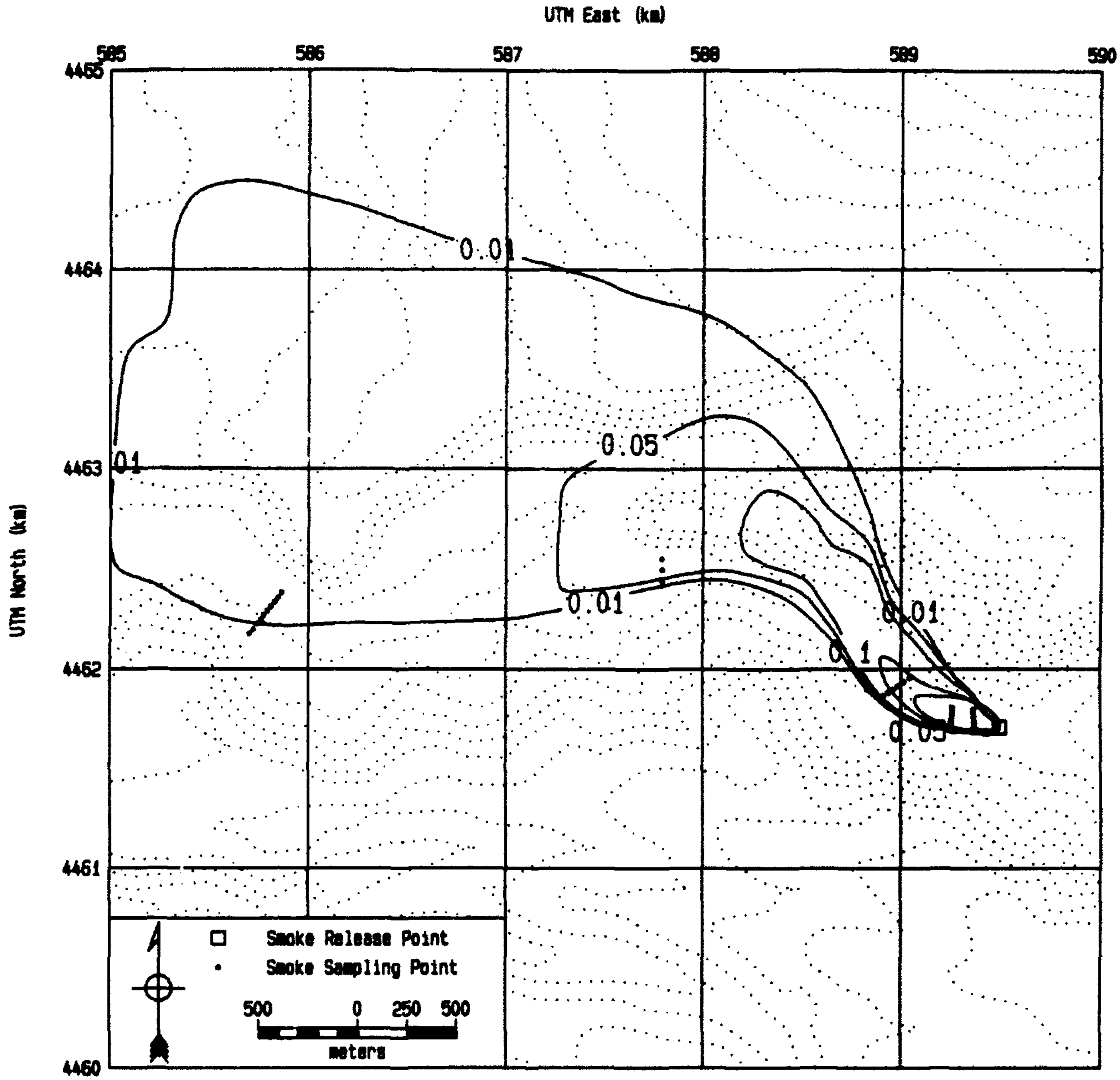


Figure 4.22 Computed Fog Oil Concentration Contours for Average Concentration for Trial 0930871 -WADOCT.

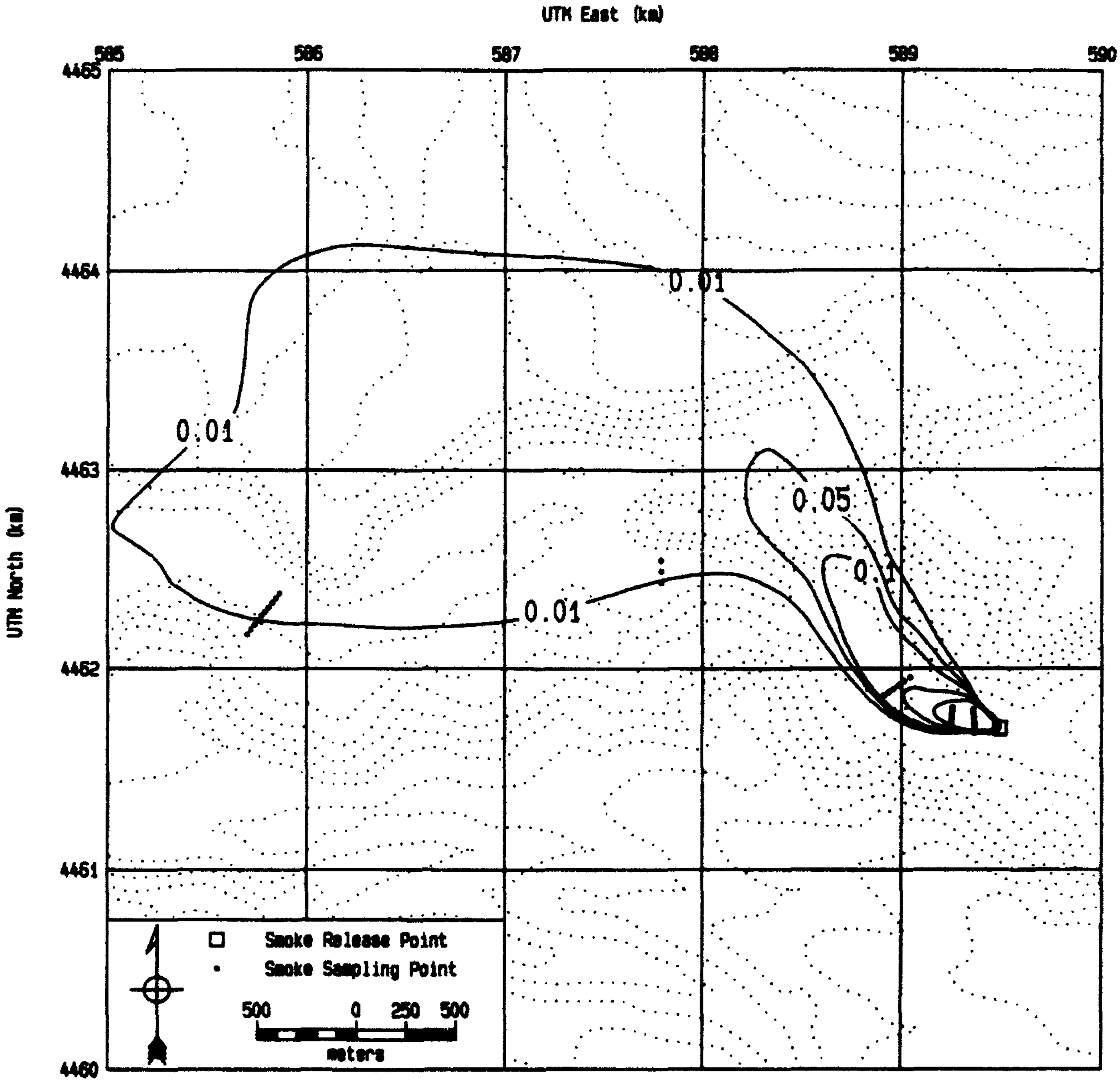


Figure 4.23 Computed Fog Oil Concentration Contours for Average Concentration for Trial 1001871 -WADOCT.

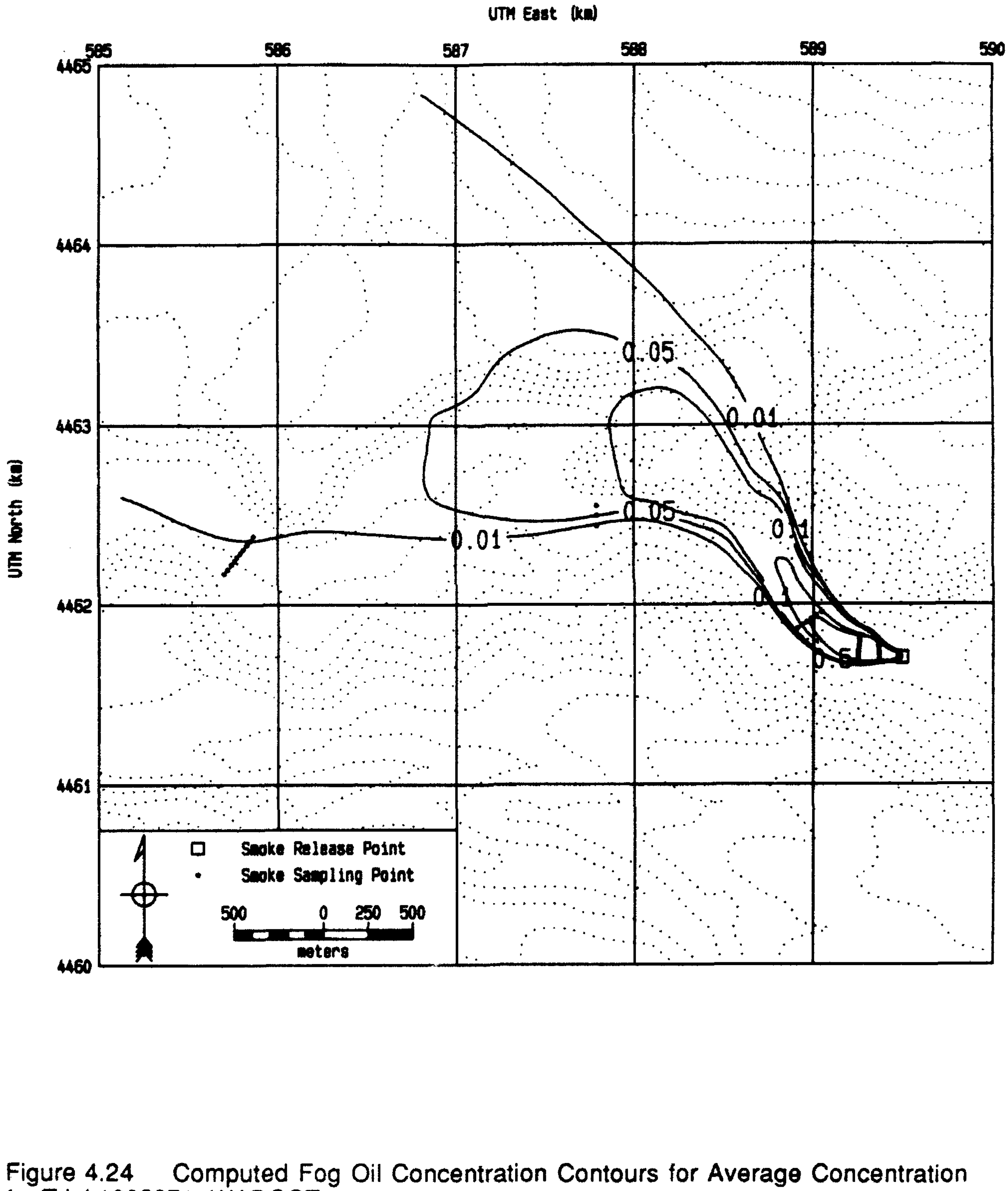


Figure 4.24 Computed Fog Oil Concentration Contours for Average Concentration for Trial 1002871 -WADOCT.

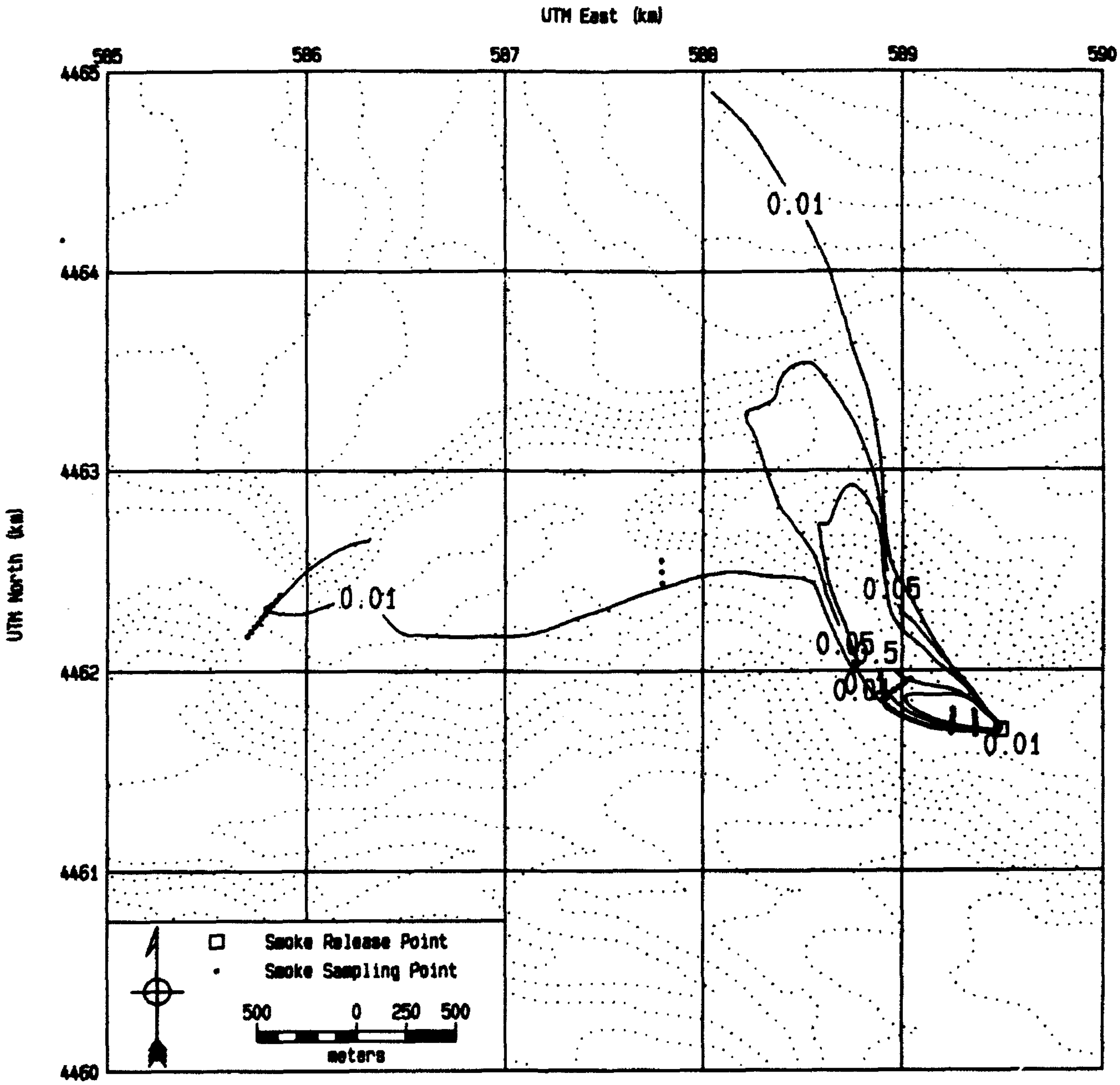


Figure 4.25 Computed Fog Oil Concentration Contours for Average Concentration for Trial 1003871 -WADOCT.

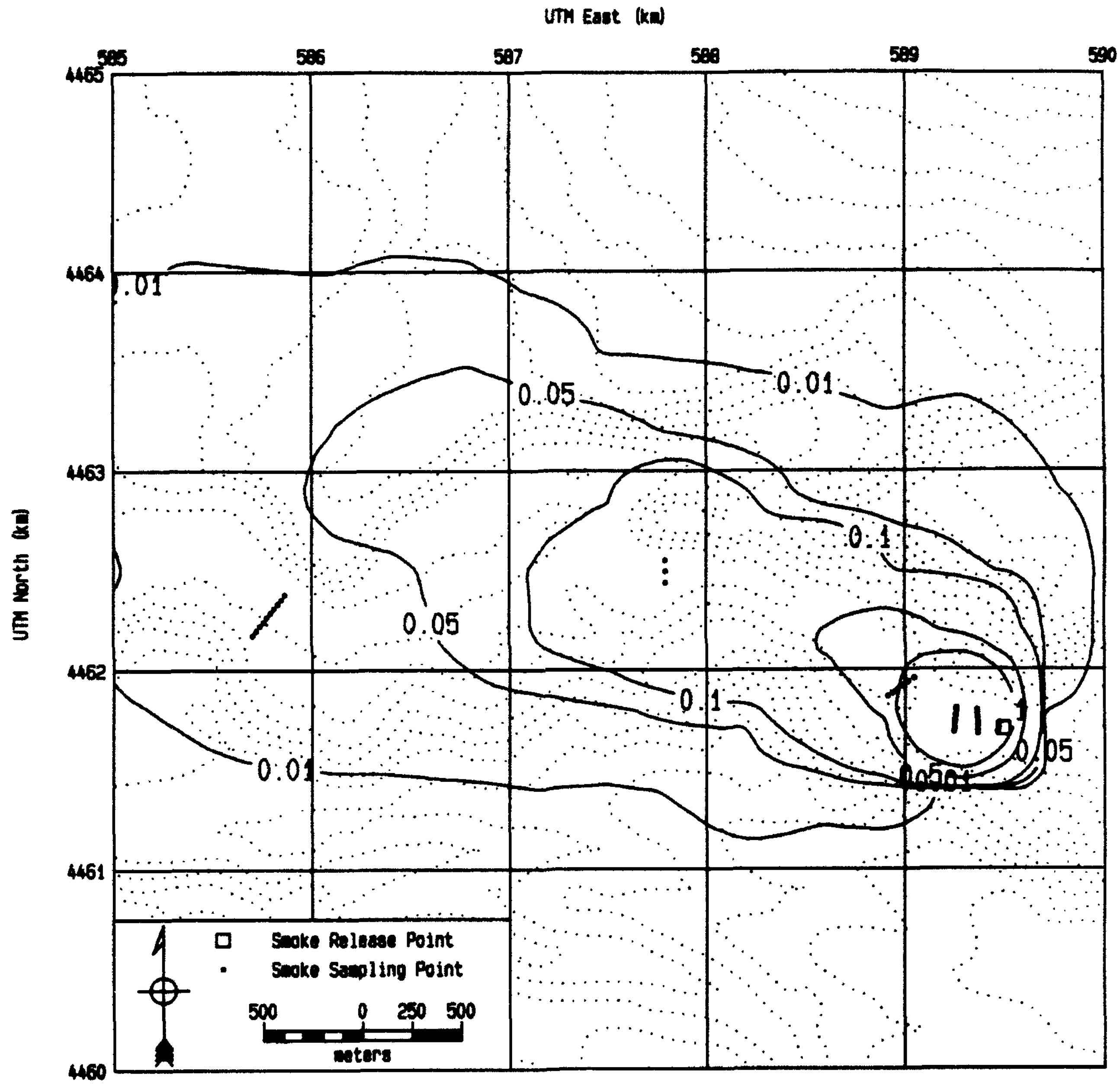


Figure 4.26 Computed Fog Oil Concentration Contours for Average Concentration for Trial 0930871 -HOTMAC.

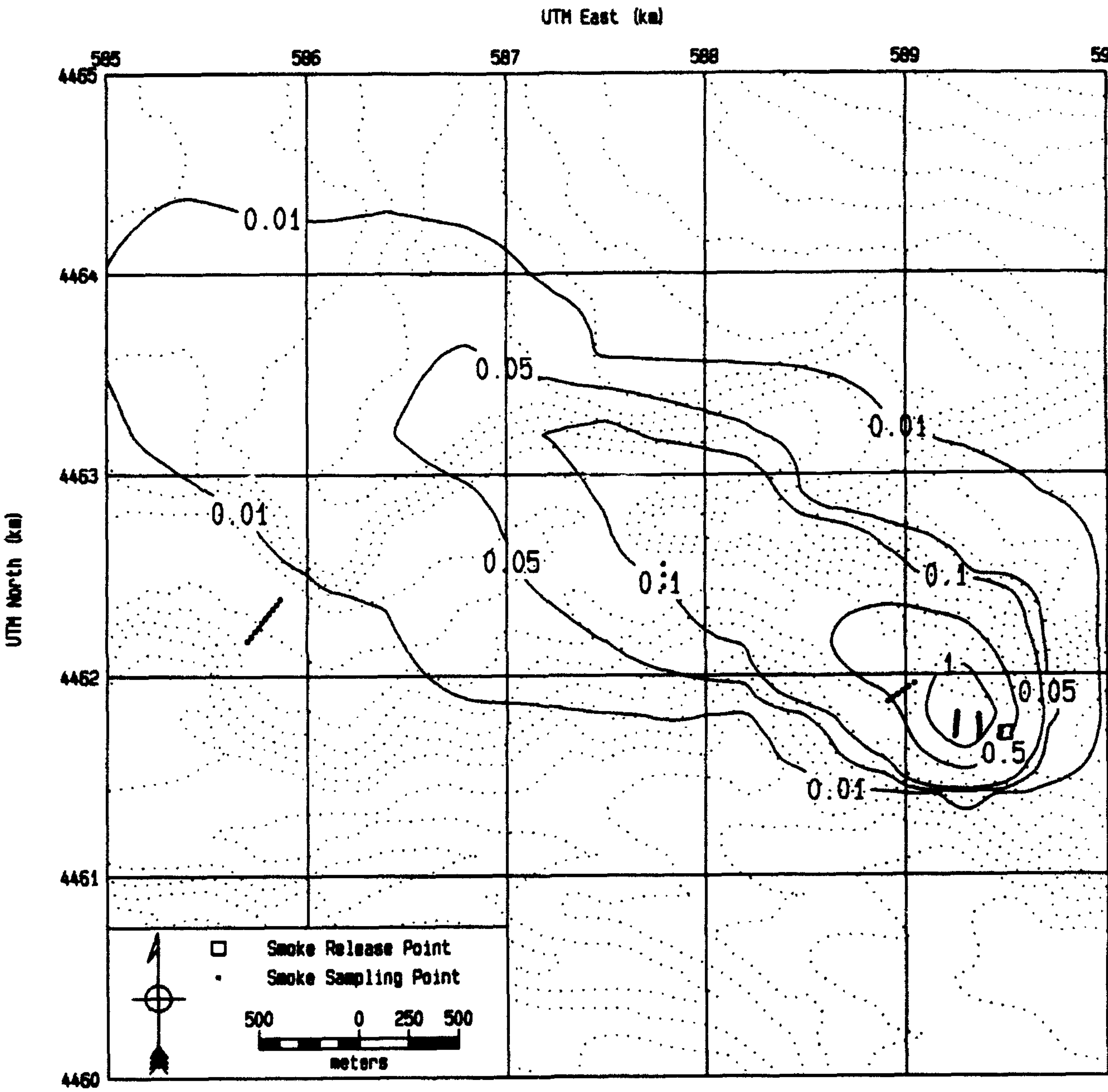


Figure 4.27 Computed Fog Oil Concentration Contours for Average Concentration for Trial 1001871 -HOTMAC.

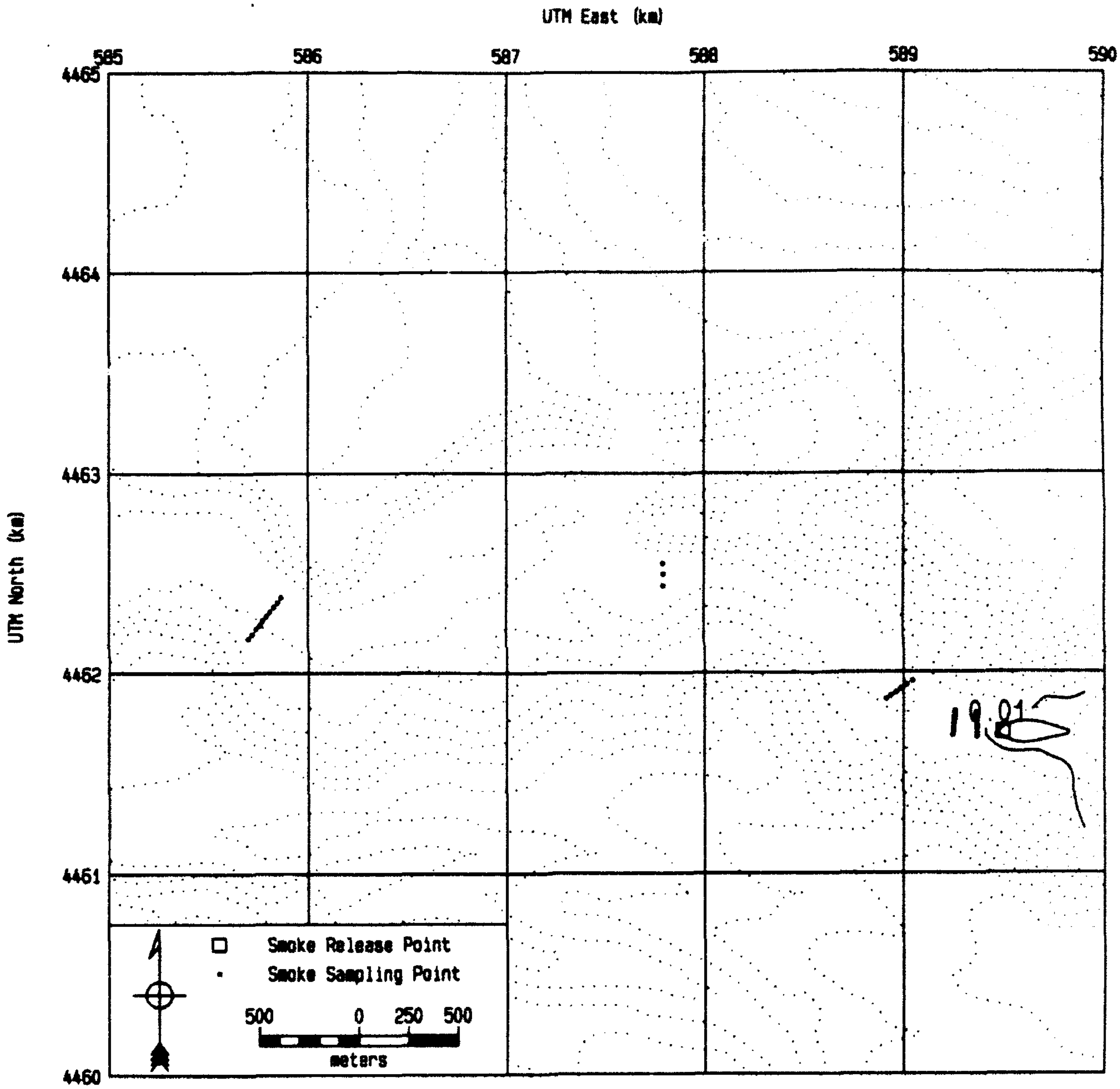


Figure 4.28 Computed Fog Oil Concentration Contours for Average Concentration for Trial 0930871 - RAMS.

zero) or a factor of about 4 if the differences are correlated with a correlation coefficient of -1. Thus, we expect a "very good" model to certainly be accurate within a factor of 4 perhaps 95% of the time. On the other hand, we consider predictions which are in error by a factor of 10 or more to be unsatisfactory. The factors of 2, 3, 4, 5 and 10 were chosen to span the range from excellent to unacceptable using five different levels of performance. It should be recognized that testing models on a paired space and time basis (as was done here) is a difficult test for the models. Accuracies within a factor of two 25% of the time (on a paired space and time basis) for general air quality models (e.g., pollutant release from a stack for distances up to about 5 km) is quite common.

Table 4.1 Percentages of Model Predictions Within a Given Factor of the Data for the Seven Stable Trials Conducted during the AMADEUS Field Study.

Trial 0930871

Factor	WADOCT	HOTMAC/RAPTAD
2	26	36
3	38	47
4	44	62
5	51	72
10	75	85

Trial 1001871

Factor	WADOCT	HOTMAC/RAPTAD
2	24	31
3	41	48
4	46	58
5	51	59
10	68	68

Pointwise comparison of model predictions with field measurements from a single trial is perhaps the most stringent test of predictive capability, and this fact may account, at least in part, for the relatively poor showing of the models. The discussion which follows explains why we feel that pointwise comparisons are indeed the most stringent, and both justifies and qualifies the above general statement.

First, it must be noted that pointwise comparisons are necessarily selective because they include only those points where sampling masts are located. Although every effort is made to select sampling locations which will yield a good representation of the plume, total success in this endeavor is virtually impossible due to the unpredictable nature of atmospheric conditions.

A second closely related issue concerns the sensitivity of pointwise comparisons to errors in wind direction. These errors may be either errors of measurement or errors of prediction. In either case, the effect on pointwise comparisons can be profound owing to the strong lateral gradients in the concentration field. For the sake of better understanding model performance, it is essential to differentiate between predicting concentration decay and predicting plume trajectory. Our experience is that models typically have problems in both these areas, but that errors in predicting plume trajectory are more severe in their impact on pointwise comparison for the above noted reason. Other measures of model performance such as centerline concentration decay or areas of concentration exceedance are much less sensitive to wind direction errors.

From a practical viewpoint however, small trajectory errors are somewhat less important than are errors in predicting concentration decay. Consider that, in evaluating health effects, one cannot take "credit" for lateral concentration gradients, but rather must assume that anyone within a given range of wind directions can experience the centerline concentration. Likewise, in designing a smoke screen, one cannot count on the wind to cooperate. Thus, one must lay out a line of smoke generators such that the target area will experience a concentration great enough to maintain the desired level of obscuration as long as the wind direction falls within a certain sector. The density of smoke generators along that line must, in turn, be adjusted to achieve the required source strength. In either case, it is concentration decay and area of concentration exceedance which are most important.

Even though errors in predicting trajectory are of somewhat less practical importance than are errors in predicting concentration decay, one cannot simply be satisfied with getting the "pattern" right. Indeed, a good complex terrain model must be able to predict wind direction correctly, and, as noted above, the models tested here seem to have serious shortcomings in this important area. At the same time, we must be careful not to overlook any positive results which may be obscured by the very poor comparison between model predictions and experimental data on a pointwise basis.

4.2.2 Discussion of Individual models

4.2.2.1 WADOCT

The WADOCT model was run for all seven of the AMADEUS stable trials (with concentrations for Trials 0927871 and 0927872 presented together). As shown in Figures 4.1 - 4.7, the WADOCT model predicts the observed winds reasonably well at the majority of the 10-m surface stations. Near surface stations A103, A104, A109 and A113, the WADOCT model does not appear to be able to accurately predict the wind field that is observed to flow down the terrain gradient into the valley. Those winds seem to be consistently predicted incorrectly. Predictions shown in Figure; 4.1 - 4.7 were carried out using data from surface stations A106, A107, A108 and A112 as input to the model.

The average concentrations predicted by WADOCT (Figures 4.12 - 4.17) appear to slightly overpredict close to the source, and then greatly underpredict by about an order of magnitude at Transects No. 5 and No. 6. While the trends between the data and the model predictions appear similar, the predicted plume centerline at Transects Nos. 2, 3, and 4 appears to diverge from the apparent centerline of the data in most cases. The constant value of the predicted concentration as a function of lateral distance at Transect No. 1 for all trials (except the combined Trials 0927871 and 0927872 which it is not presented) is due to the fact that the WADOCT model is not structured to predict these close-in receptors. The WADOCT computer code was developed to predict contours of constant concentration, with an upper bound on the magnitude of concentration. The model was modified by the present authors to allow for interpolation of the predicted contours in order to determine the concentration at specific receptors within the contours. However, the WADOCT model is not designed

to predict concentrations within 100 m from the source, therefore predictions at Transect No. 1 cannot be determined.

The underprediction at Transects No. 5 and No. 6 is due to the fact the trajectory of the predicted plumes is further to the north-west than the observed plume. The observed plume appears to be evenly mixed within the valley and does not appear to disperse above the height of the valley walls, as is evident in Figure 4.11. We can test this theory with a simple calculation. If we assume that the plume is uniformly dispersed within the valley, but vertically contained within that valley (as shown in Figure 4.11), then we can compute a well-mixed concentration given the fog-oil release rate, the height of the valley, the width of the valley and the wind speed in the valley. Examining Figures 3.1 and 4.11, we can reasonably approximate the cross sectional area of the valley at Transect No. 6 as an equivalent rectangle of width 800 meters and of height 400 ft. (133 meters), giving a cross sectional area (A) of 106,400 m^2. If we divide the release rate by the wind speed at surface station No. A111 for each of the various tests (see Table 3.1) and then by the cross sectional area (A), we can then approximate what the well-mixed concentration should be in the valley, assuming that none of the fog-oil escapes above the 133 meter height of the valley walls.

Table 4.2 compares the well-mixed concentrations calculated assuming a uniformly-mixed plume that is contained within the valley with the measured concentrations for Trials 0930871, 1001871 and 1003871 (these were the only three trials where Transect No. 6 was used). As is evident from the information in the table, the calculated concentrations are well within 10% of the measured concentrations for Trials 0930871 and 1001871, and within a factor of two for Trial 1003871, which lends support to the theory that the plume remained in the valley and did not disperse significantly above the elevation of the top of the valley walls. Table 4.2 also compares the well-mixed assumption with the average values predicted by WADOCT and HOTMAC/RAPTAD at Transect No. 6.

Table 4.2 Comparison of Well-Mixed Assumption with Measured Concentrations and Model Prediction for Transect No. 6.

Trial No.	"Mixed" Concentration (mg/m3)	Measured Concentration (mg/m3)	WADOCT Concentration (mg/m3)	HOTMAC Concentration (mg/m3)
0930871	0.125	0.133	0.015	0.027
1001871	0.105	0.102	0.009	0.006
1003871	0.088	0.161	0.007	N.A.

The computed fog-oil concentration contours, as predicted by the WADOCT model, all appear to reasonably predict the observed plume (see Figures 4.19 - 4.25). One area where the contours appear to be consistently divergent from the measured data is near surface station A107, where the center of the plume is rising up the terrain to the north-east of station A107. This tendency can be attributed to the fact that the wind field prediction did not correctly indicate that the wind would not flow down that same valley wall.

Since the optimal choice of surface station locations to use as input into the WADOCT model was not known a priori, a sensitivity study was performed. Figures 4.4, 4.29, and 4.30 show the resultant wind-field predictions using three different sets of input: (1) the 4 towers in line with the dispersion (the baseline case), (2) all of the towers as inputs, and (3) station A108 alone. Figures 4.14, 4.31, and 4.32 show the resultant fog-oil concentration contours using, respectively, these same three different sets of input: (1) the 4 towers in line with the dispersion (the baseline case), (2) all of the towers as inputs, and (3) station A108 alone. As is evident from these figures, the choice of station(s) is not very significant.

4.2.2.2 HOTMAC/RAPTAD

The HOTMAC/RAPTAD models were run for two of the seven AMADEUS stable trials (Trials 0930871 and 1001871). As shown in Figures 4.8 and 4.9, the HOTMAC model predicts quite well the observed winds at the majority of the 10-m surface stations. In

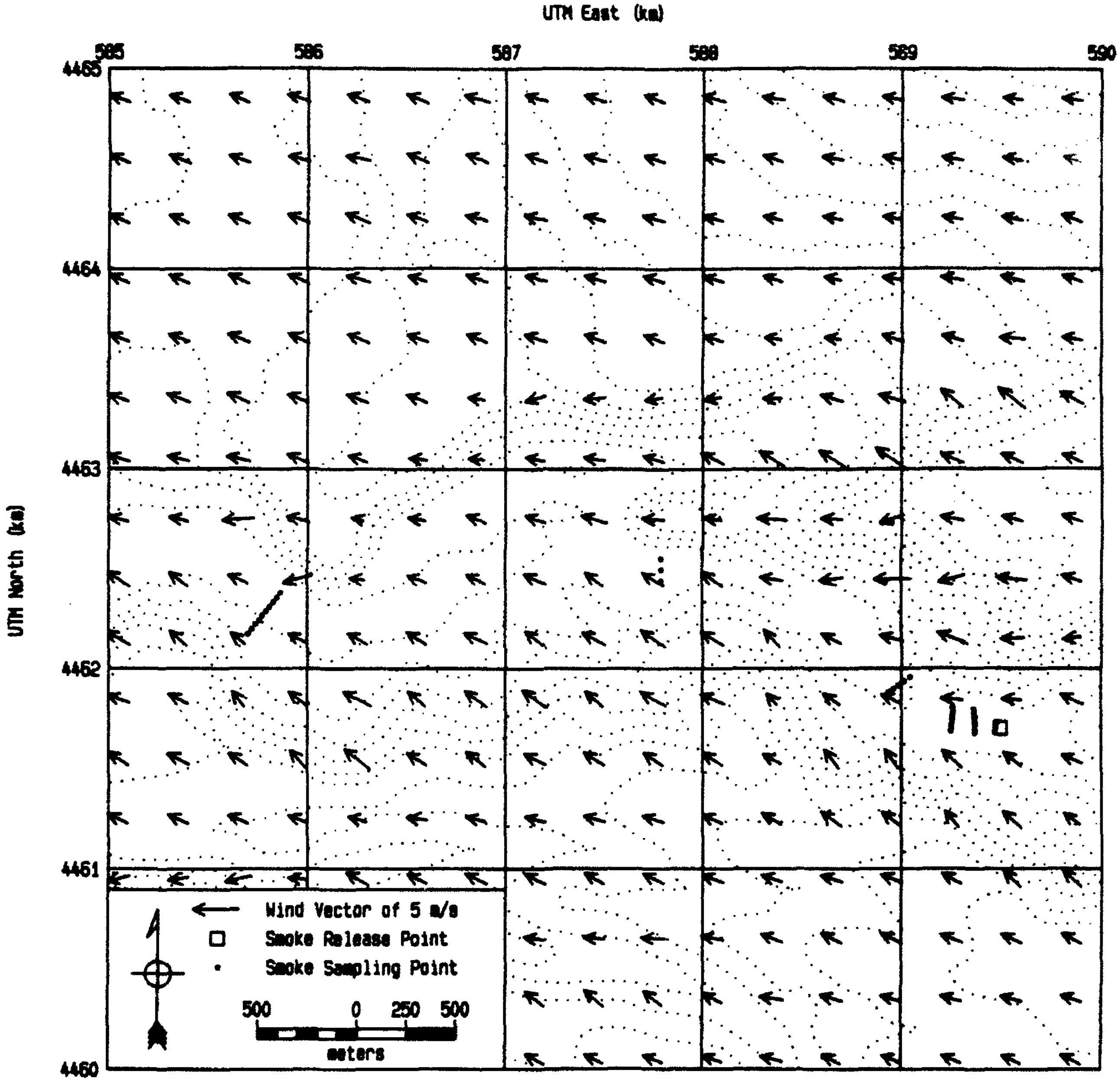


Figure 4.29 Computed Wind Field and Observed Wind Field for Average Concentration for Trial 0930871, using Data from Surface Station A108 - WADOCT.

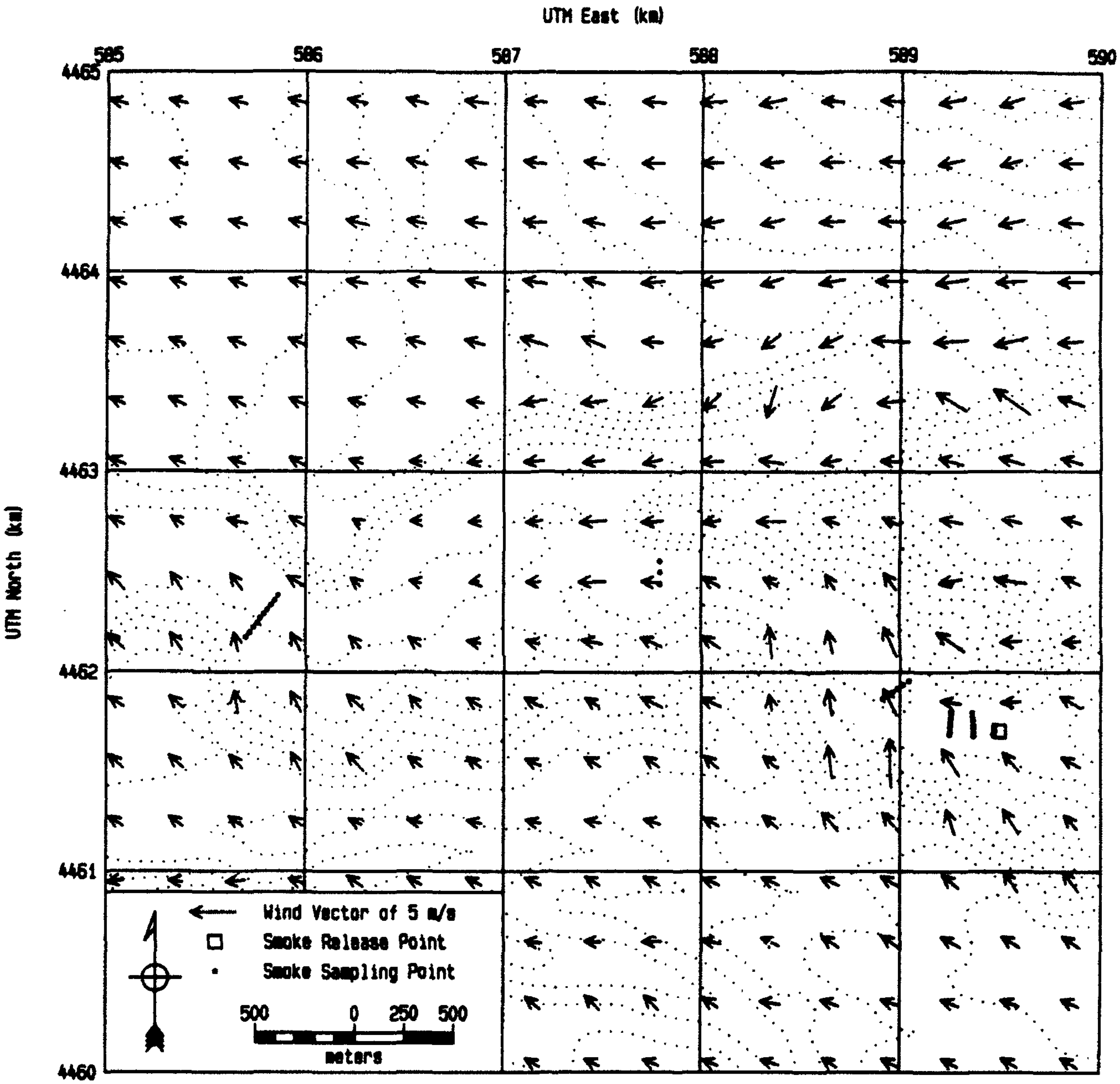


Figure 4.30 Computed Wind Field and Observed Wind Field for Average Concentration for Trial 0930871, using Data from all Surface Stations - WADOCT.

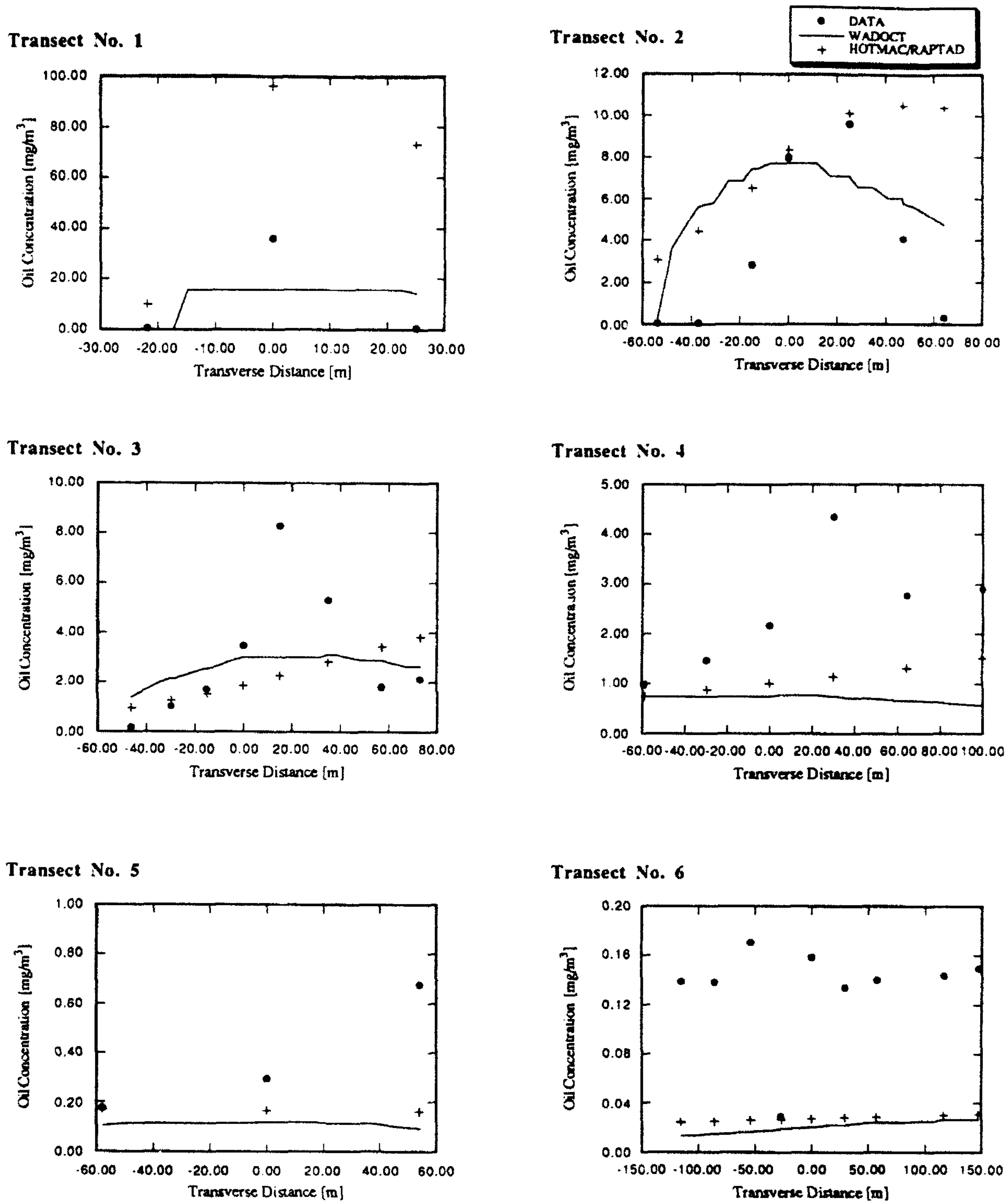


Figure 4.31 Comparison of the WADOCT and HOTMAC/RAPTAD Model Predictions with Average Concentration Data for Trial 0930871 (using only Data from Surface Station A108 for the WADOCT Predictions).

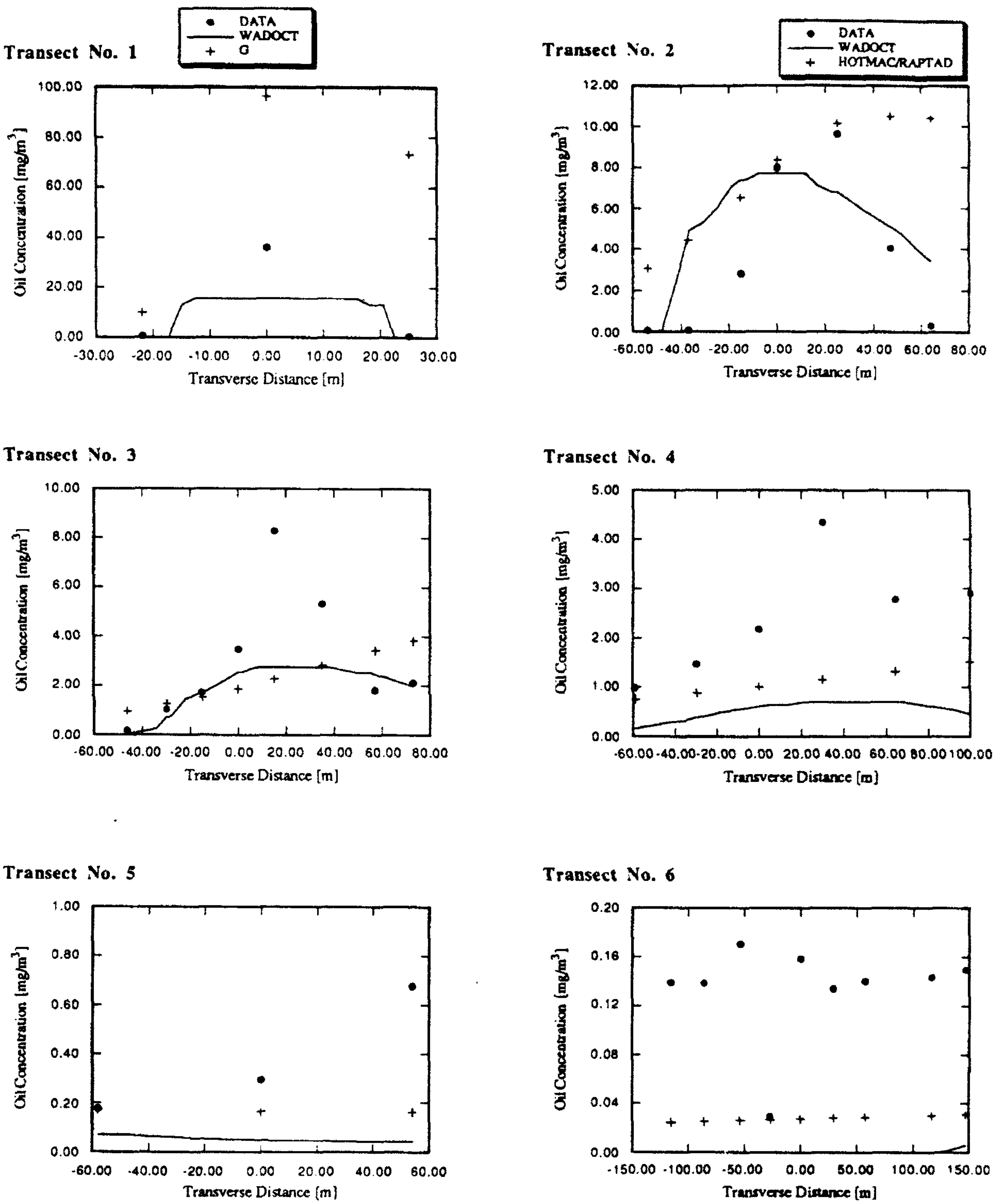


Figure 4.32 Comparison of the WADOCT and HOTMAC/RAPTAD Model Predictions with Average Concentration Data for Trial 0930871 (using Data from all Surface Stations for the WADOCT Predictions).

both trials, the wind fields around Stations A104, and to a lesser degree A109 for Trial 1001871, fail to predict the wind flow down the terrain gradient as observed with the surface station measurements.

The concentrations along the transects as predicted by RAPTAD for Trials 0930871 and 1001871 (Figures 4.14 and 4.15) appear to: (1) overpredict close to the source (Transects No. 1), (2) predict c. ɜe in magnitude to the data for Transect Nos. 2, 3, 4 and sometimes 5, and (3) predict low by about one order of magnitude at Transect No. 6. While the magnitude of the RAPTAD predictions along the transect are better than the WADOCT predictions (about 47-48% of the predictions are within a factor of 3 of the data, compared with 38-41% for WADOCT) the behavior of the RAPTAD predictions do not reflect the trends of the data. The data, in general, tends to have an almost symmetric distribution about the center of the transects (for Transects Nos. 1, 2, 3 and 4), whereas the RAPTAD model predicts an increasing concentration from the south or south-east ends to the north or north-west ends of those respective transects.

Figures 4.26 and 4.27 show the RAPTAD predicted concentration contours for Trials 0930871 and 1001871, respectively. These two figures help to emphasize the fact that while the magnitude of the predictions are reasonable, the location of the centerline of the plume is divergent from the observation. The predicted plume does not appear to follow the terrain very well, and the width of the 0.01 mg/m3 contour is far greater than would be expected given that the observed plume was contained within the valley, and that the observed wind field would not have had flow upwind behind the source and as far to the north-east or south-west as RAPTAD predicted.

4.2.2.3 RAMS

When the RAMS computer code was run, a significant limitation of the model was uncovered. As Figure 4.10 indicates, the predicted wind field at the ground-level was in the opposite direction to the observed wind field. It is obvious that the 60-m vertical resolution was not fine enough to resolve the shallow downslope surface flow.

Even if RAMS could accurately predict the drainage flow into the valley, the low vertical resolution would make it difficult to predict accurate smoke concentrations. This low resolution implies that a smoke release is immediately mixed to a depth of 60 m as soon as discharged. The observed plume, however, was typically less than

10 m thick in the region of the near-field sampling stations. As would be expected, in case 0930871, the close-in concentrations predicted by RAMS tended to be low by approximately two orders of magnitude (see Figure 4.28).

It appears from these results that the option of nesting grids vertically would be required in order to simulate these smoke tests. This would allow a greater vertical resolution on the horizontally finer nested grids. However, this capability was not implemented in the version of RAMS used in this study. A new (beta test) version is under development and should support this capability. A copy of a new version of RAMS (as a non-verified test model) was received, but unfortunately efforts to use the beta-test version of this model were unsuccessful.

If self-similarity in the terrain roughness is assumed (i.e. the same roughness at all scales), then the greatest possible vertical resolution is proportional to the horizontal grid resolution (e.g. reducing the horizontal spacing by a factor of two would reduce the average difference in elevations between horizontal grid points by a factor of two). In theory, it is possible to obtain any desired vertical resolution by sufficiently increasing the horizontal resolution; that is, by increasing the number of grid points. In practice, the computational resources demanded by the current version of RAMS prevent this from being a viable option. RAMS was run on a Sun 4 workstation with 64 megabytes of memory. Even with a vertical resolution of 60 meters, RAMS required approximately 40 megabytes of memory and 120 hours of CPU time for each test. In order in achieve a reasonable vertical resolution, eg. 6 meters, it would be necessary to increase the horizontal resolution by a factor of 10; i.e., increase the total number of grid points by a factor of 100, with both the required memory and CPU time increasing proportionally. This would be impractical for all but, perhaps, the largest supercomputers.

While it appears that RAMS should be capable of accounting for the influence of gently sloping terrain, it became numerically unstable when applied to moderate-to-steep terrain, such as the terrain at the Meadowbrook site. RAMS could not successfully be run to model the AMADEUS fog-oil stable releases. Should a version of RAMS with vertical grid nesting capability become available in the future, it is recommended that this model be re-evaluated, assuming run times are reasonable.

While the previously mentioned instability due to steep terrain is RAMS' most serious limitation, we found that the model is sensitive to many of its input parameters. We were unable to achieve reasonable results from RAMS despite a considerable investment of effort, including consultation with the developers. Figures 4.10 and 4.28 illustrate the computed wind field and dispersion pattern from the most successful model execution. Since the sounding used to initialize the model did not contain any southerly winds, the computed wind field, which is dominated by southerly winds, appears unrealistic. The computed wind field differs radically from that which would be expected given the initial conditions; therefore it is believed that the difference stems from a failure in the model's numerical integration algorithm, and that the underlying equations would produce quite different results once successful integration has occurred. It remains to be determined whether RAMS is theoretically capable of resolving the shallow downslope surface flow with a vertical grid resolution of 60 meters.

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5. SUMMARY AND CONCLUSIONS

Three wind field/dispersion models (the WADOCT, HOTMAC/RAPTAD and RAMS models) were tested with field data on smoke dispersion in complex terrain obtained from the AMADEUS Dispersion Experiments. The AMADEUS Dispersion Experiments were carried out at the Meadowbrook site, in northern California, during Phase IV of Project WIND. The AMADEUS study consisted of a total of 7 fog-oil smoke-dispersion experiments conducted in stable conditions and 5 experiments conducted in unstable conditions. The purpose of this report is to evaluate the performance of the most promising complex terrain dispersion models for distance scales on the order of 25 m to 4 km. The comparisons in this report consider only the 7 stable experiments. The 5 unstable releases were not considered because those plumes rose off the ground soon after release from the smoke generator. Moreover, the main interest of the Army is smoke dispersion scenarios that would present potential health hazards to troops during training exercises and the worse case would occur under stable meteorological conditions.

The Meadowbrook site is located approximately 20 miles east of Red Bluff, California in the foothills of the Sierra-Nevada Mountains, and consists of a forked creek valley with surrounding slopes rising to a height of about 250 m above the valley floor. The meteorology of the site is dominated by a density-driven, diurnal upslope-downslope flow pattern typical of mountain/valley topography. The field data include average concentration measurements on five or six transects (depending on the trial) out to distances of about 4 km. In addition, the data base includes time-averaged source measurements as well as meteorological data from thirteen 10-m instrument towers, a 30-m tower and a 2-m mast.

The WADOCT, HOTMAC/RAPTAD, and RAMS models represent the state-of-the-art wind field/dispersion models that are applicable to the time and distance scales of the AMADEUS experiments. These three models were the only operational models that were found that meet the selection criteria for use with the AMADEUS dispersion data. In addition, the three models covered the range of modeling approaches from simple to complex. Each of the three models predict the wind field first, from which smoke dispersion is computed. The WADOCT model treats the release as a Gaussian plume which is transported and dispersed downwind with a horizontally-uniform wind speed. The HOTMAC/RAPTAD model and the RAMS models are complex finite-difference

solutions to the governing primitive equations for flow in complex terrain with complex dispersion models added to the wind field models. The HOTMAC/RAPTAD model employs the hydrostatic and Boussinesq approximations and is a less complex model as compared to RAMS. The WADOCT model runs on a PC, whereas the HOTMAC/RAPTAD and RAMS models require computer workstations.

The meteorology and the fog-oil concentration measurements are similar between the various stable trials. Concentration data used and presented here have been updated from previously reported values (DeVaull, 1990) to account for variations in oil loss with dosage and time spent in the cassette. Previously reported values assumed uniform oil loss, but closer examination of the data showed this assumption to be poor.

The WADOCT model predictions were compared with all 7 stable releases, and the HOTMAC/RAPTAD models were compared for two trials. The WADOCT model was not developed for predictions less than 100 m downwind and therefore, did not predict the first transect well (about 25 m downwind). Both the WADOCT and HOTMAC/RAPTAD models predicted the 2nd and 3rd transects reasonably well and underpredicted the remaining transects. At the final transect, No. 6, the underprediction was significant (about one order of magnitude). This underprediction results from the models failure to simulate the constraining effects of the valley wall on the plume trajectory and the limited horizontal plume growth. In addition, the observed concentrations show a significant variation in concentration between the 2-m and 8-m levels in the first 3 transects. Neither the WADOCT model nor the HOTMAC/RAPTAD models predicted this observation.

While the concentrations predicted by HOTMAC/RAPTAD are closer to the observed data, the model does not predict the plume centerline as well as the WADOCT model. The location and spreading of the HOTMAC/RAPTAD plume was off-center from the observed plume.

The RAMS model failed to predict even a reasonable wind field in the valley for these trials. This is primarily due to the fact that the resolution of the vertical grid spacing could not be reduced enough to distinguish the drainage flow in the valley from the synoptic wind. To permit a very refined vertical grid spacing needed for this analysis, literally years of computer time would be required on our high-end Sun workstation. It

is hoped that the version of RAMS which is currently in the developmental phase will be able to more adequately handle these trials.

In evaluating model performance, one must recognize that the meteorological and source data which serve as inputs to the models and the concentration data to which the model predictions are compared both contain considerable experimental uncertainty. Not only are there the uncertainties associated with the experimental procedures which are in themselves difficult to carry out under field test conditions, there is the added fact that each trial represents a single realization of a process which itself has a large statistical variance. Thus, although the models can be significantly improved in many respects, their current performance must be viewed in the proper light.

Finally, general conclusions about model performance for these models in complex terrain are not warranted from this study alone as it focused on one site and only stable meteorological conditions. Only after more model/data comparisons at characteristically different sites can a more refined picture of model performance in complex terrain be made for these models. This study provides an interesting depiction of the successes and disappointments of the use of current generation complex terrain dispersion models at sites similar to the Meadowbrook site in California.

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Appendix A Synopsis of Surface-Station Data for Stable Releases

Table A.1 Synopsis of surface-station data for Test 0925871. Smoke was released from 00:18 to 01:03. The stable release point was used.

Station	S [m/s]	U [m/s]	θ [°]	σ_θ [°]	T_{10m} [°C]	T_{2m} [°C]	T_{soil} [°C]	Ri_b
A101	1.182	1.099	121.7	22.36	16.41	15.65	14.67	0.204
A102	0.389	0.328	66.64	48.47	15.59	14.20	12.76	3.308
A103	-99999	-99999	-99999	-99999	-99999	N/A	N/A	N/A
A104	2.770	2.641	52.73	17.08	15.62	N/A	N/A	N/A
A105	2.370	2.332	118.6	10.28	17.29	17.02	17.80	0.021
A106	2.079	1.967	88.00	21.51	16.51	16.00	18.17	0.046
A107	1.622	1.550	165.5	17.07	15.99	15.17	15.92	0.116
A108	1.932	1.889	114.4	11.76	15.27	14.29	17.08	0.097
A109	1.954	1.944	55.65	10.94	19.53	19.25	17.84	0.031
A110	2.002	1.978	96.37	9.143	18.90	18.45	18.73	0.044
A111	0.324	0.323	190.2	0.208	N/A	N/A	N/A	N/A
A112	3.085	3.070	155.8	5.585	N/A	N/A	N/A	N/A
A113	3.041	3.011	99.96	8.009	N/A	N/A	N/A	N/A
A114	0.468	0.385	71.66	53.36	15.56	14.35	N/A	1.578
A115	1.307	1.291	66.47	10.46	16.24	14.35	N/A	N/A

Notes:

1. All wind speed and direction measurements are at 10 m, except for Station A115 which is at 30 m.
2. All upper temperature measurements (T_{10m}) are at 10 m as implied by the subscript, except for Station A114 which is at 8 m and Station A115 which is at 30 m.
3. All lower temperature measurements (T_{2m}) are at 2 m as implied by the subscript.
4. Soil temperature measurements (T_{soil}) are a depth of 0.1 m.
5. 1 bad minute was excluded in computing the 2-m temperature for Station A114.
6. 3 bad minutes were excluded in computing the 10-m temperature for Station A114.
7. 1 bad minute was excluded in computing the 10-m temperature for Station A115.
8. 2 bad minutes were excluded in computing the 10-m temperature for Station A115.

Table A.2 Synopsis of surface-station data for Test 0927871. Smoke was released from 03:19 to 03:39. The stable release point was used.

Station	S [m/s]	U [m/s]	θ [°]	σ_θ [°]	T_{10m} [°C]	T_{2m} [°C]	T_{soil} [°C]	Ri_b
A101	1.055	0.920	117.6	28.17	13.23	11.75	8.263	0.480
A102	0.348	0.218	91.02	69.02	11.50	9.928	5.349	4.696
A103	2.880	2.821	64.33	11.94	12.77	N/A	N/A	N/A
A104	3.819	3.741	54.14	11.27	12.55	N/A	N/A	N/A
A105	2.251	2.216	113.5	10.01	16.76	16.06	13.35	0.052
A106	2.019	1.959	103.1	19.10	12.60	11.38	13.00	0.110
A107	1.371	1.325	139.0	15.14	12.04	10.27	9.758	0.339
A108	1.866	1.833	98.54	10.70	11.95	9.737	11.61	0.226
A109	0.868	0.746	20.11	32.54	21.65	20.87	12.93	0.377
A110	0.646	0.555	138.0	35.80	19.70	17.82	14.24	1.571
A111	2.507	2.392	145.4	17.44	N/A	N/A	N/A	N/A
A112	2.101	2.059	156.8	14.50	N/A	N/A	N/A	N/A
A113	3.483	3.457	86.30	7.269	N/A	N/A	N/A	N/A
A114	0.671	0.556	74.32	36.88	11.42	9.235	N/A	1.372
A115	1.213	1.124	13.47	23.32	13.05	9.235	N/A	N/A

Notes:

1. All wind speed and direction measurements are at 10 m, except for Station A115 which is at 30 m.
2. All upper temperature measurements (T_{10m}) are at 10 m as implied by the subscript, except for Station A114 which is at 8 m and Station A115 which is at 30 m.
3. All lower temperature measurements (T_{2m}) are at 2 m as implied by the subscript.
4. Soil temperature measurements (T_{soil}) are a depth of 0.1 m.
5. 3 bad minutes were excluded in computing the 10-m temperature for Station A115.

Table A.3 Synopsis of surface-station data for Test 0927872. Smoke was released from 06:44 to 06:54. The stable release point was used.

Station	S [m/s]	U [m/s]	θ [°]	σ_θ [°]	T_{10m} [°C]	T_{2m} [°C]	T_{soil} [°C]	Ri_b
A101	1.232	1.079	132.3	31.24	11.56	10.39	6.403	0.283
A102	0.648	0.425	98.63	51.68	9.870	8.232	3.937	1.418
A103	-99999	-99999	-99999	-99999	-99999	N/A	N/A	N/A
A104	3.601	3.568	57.50	7.609	10.67	N/A	N/A	N/A
A105	2.227	2.178	113.9	12.35	15.72	14.96	11.88	0.057
A106	2.836	2.780	99.05	11.61	11.86	10.98	11.52	0.041
A107	1.818	1.765	146.9	13.74	10.51	8.841	7.890	0.183
A108	2.562	2.541	102.0	7.438	9.763	7.847	10.05	0.105
A109	1.338	1.311	114.6	21.87	20.28	19.25	10.93	0.208
A110	2.002	1.994	146.9	5.190	18.02	16.39	13.11	0.144
A111	2.402	2.232	158.0	23.00	N/A	N/A	N/A	N/A
A112	3.096	3.077	157.8	6.425	N/A	N/A	N/A	N/A
A113	3.100	3.062	82.58	9.310	N/A	N/A	N/A	N/A
A114	1.022	0.901	76.79	32.00	9.635	8.253	N/A	0.393
A115	1.509	1.488	9.496	9.026	11.59	8.253	N/A	N/A

Notes:

1. All wind speed and direction measurements are at 10 m, except for Station A115 which is at 30 m.

2. All upper temperature measurements (T_{10m}) are at 10 m as implied by the subscript, except for Station A114 which is at 8 m and Station A115 which is at 30 m.

3. All lower temperature measurements (T_{2m}) are at 2 m as implied by the subscript.

4. Soil temperature measurements (T_{soil}) are a depth of 0.1 m.

5 1 bad minute was excluded in computing the vector speed and direction for Station A109.

Table A.4 Synopsis of surface-station data for Test 0930871. Smoke was released from 06:48 to 07:28. The stable release point was used.

Station	S [m/s]	U [m/s]	θ [°]	σ_θ [°]	T_{10m} [°C]	T_{2m} [°C]	T_{soil} [°C]	Ri_b
A101	1.528	1.441	121.9	19.15	18.89	17.12	12.07	0.265
A102	0.946	0.853	78.45	26.80	18.02	15.25	9.410	1.072
A103	2.531	2.453	82.01	13.71	18.09	N/A	N/A	N/A
A104	3.000	2.862	42.17	16.26	17.73	N/A	N/A	N/A
A105	3.110	3.048	116.3	11.39	20.81	20.12	16.75	0.026
A106	3.217	3.161	79.98	10.83	19.61	18.79	16.72	0.029
A107	1.942	1.854	159.7	17.43	18.34	15.83	13.11	0.231
A108	2.405	2.329	112.4	14.75	17.21	14.55	14.19	0.160
A109	-99999	-99999	-99999	-99999	-99999	-99999	-99999	-99999
A110	1.712	1.688	112.4	9.821	25.20	23.22	17.60	0.231
A111	3.137	3.037	155.9	14.54	N/A	N/A	N/A	N/A
A112	3.746	3.730	158.3	5.228	N/A	N/A	N/A	N/A
A113	4.410	4.295	94.20	13.11	N/A	N/A	N/A	N/A
A114	1.465	1.391	74.19	19.69	17.79	15.41	N/A	0.306
A115	2.052	2.005	74.27	13.22	18.96	15.41	N/A	N/A

Notes:

1. All wind speed and direction measurements are at 10 m, except for Station A115 which is at 30 m.
2. All upper temperature measurements (T_{10m}) are at 10 m as implied by the subscript, except for Station A114 which is at 8 m and Station A115 which is at 30 m.
3. All lower temperature measurements (T_{2m}) are at 2 m as implied by the subscript.
4. Soil temperature measurements (T_{soil}) are a depth of 0.1 m.

Table A.5 Synopsis of surface-station data for Test 1001871. Smoke was released from 06:52 to 07:32. The stable release point was used.

Station	S [m/s]	U [m/s]	θ [°]	σ_θ [°]	T_{10m} [°C]	T_{2m} [°C]	T_{soil} [°C]	Ri_b
A101	1.359	1.216	119.4	26.82	20.32	18.56	14.08	0.332
A102	0.944	0.770	93.50	52.05	19.32	17.55	11.35	0.696
A103	2.252	2.009	91.60	28.82	19.80	N/A	N/A	N/A
A104	3.922	3.642	52.45	22.01	20.36	N/A	N/A	N/A
A105	2.803	2.742	120.6	12.08	21.98	21.31	17.79	0.032
A106	3.438	3.313	78.56	18.52	20.53	20.12	18.73	0.014
A107	2.322	2.225	161.2	16.78	19.27	18.20	14.86	0.071
A108	2.745	2.669	112.1	13.56	18.02	16.13	15.49	0.088
A109	2.949	2.926	61.08	11.35	27.33	26.31	19.28	0.041
A110	1.979	1.762	100.8	32.83	24.80	23.29	19.55	0.133
A111	2.787	2.686	148.0	15.32	N/A	N/A	N/A	N/A
A112	3.733	3.693	157.5	8.690	N/A	N/A	N/A	N/A
A113	4.103	3.716	90.89	26.16	N/A	N/A	N/A	N/A
A114	1.379	1.221	81.78	28.83	19.05	17.45	N/A	0.234
A115	2.243	2.197	80.74	12.32	20.25	17.45	N/A	N/A

Notes:

1. All wind speed and direction measurements are at 10 m, except for Station A115 which is at 30 m.
2. All upper temperature measurements (T_{10m}) are at 10 m as implied by the subscript, except for Station A114 which is at 8 m and Station A115 which is at 30 m.
3. All lower temperature measurements (T_{2m}) are at 2 m as implied by the subscript.
4. Soil temperature measurements (T_{soil}) are a depth of 0.1 m.

Table A.6 Synopsis of surface-station data for Test 1002871. Smoke was released from 07:17 to 07:47. The stable release point was used.

Station	S [m/s]	U [m/s]	θ [°]	σ_θ [°]	T_{10m} [°C]	T_{2m} [°C]	T_{soil} [°C]	Ri_b
A101	1.542	1.484	112.7	15.33	18.90	17.78	14.99	0.170
A102	0.745	0.685	76.10	34.68	18.01	16.33	12.46	1.067
A103	1.989	1.933	85.07	13.22	18.41	N/A	N/A	N/A
A104	3.249	3.102	51.00	17.30	18.78	N/A	N/A	N/A
A105	2.930	2.897	115.1	8.395	20.48	20.02	18.37	0.021
A106	2.157	2.068	94.06	16.23	18.73	18.11	18.11	0.050
A107	1.513	1.429	159.6	19.27	18.28	16.26	14.72	0.308
A108	1.944	1.890	104.3	13.75	17.37	15.22	15.97	0.199
A109	2.217	2.172	56.79	14.97	24.80	24.15	18.51	0.049
A110	1.409	1.374	104.5	12.76	23.16	21.94	19.37	0.216
A111	2.914	2.855	148.7	11.38	N/A	N/A	N/A	N/A
A112	3.189	3.177	157.3	5.066	N/A	N/A	N/A	N/A
A113	3.534	3.482	100.7	9.951	N/A	N/A	N/A	N/A
A114	1.257	1.219	72.34	18.44	18.01	16.78	N/A	0.220
A115	1.915	1.887	74.17	10.57	18.77	16.78	N/A	N/A

Notes:

1. All wind speed and direction measurements are at 10 m, except for Station A115 which is at 30 m.
2. All upper temperature measurements (T_{10m}) are at 10 m as implied by the subscript, except for Station A114 which is at 8 m and Station A115 which is at 30 m.
3. All lower temperature measurements (T_{2m}) are at 2 m as implied by the subscript.
4. Soil temperature measurements (T_{soil}) are a depth of 0.1 m.
5. 1 bad minute was excluded in computing the 10-m temperature for Station A111

Table A.7 Synopsis of surface-station data for Test 1003871. Smoke was released from 06:56 to 07:27. The stable release point was used.

Station	S [m/s]	U [m/s]	θ [°]	σ_θ [°]	T_{10m} [°C]	T_{2m} [°C]	T_{soil} [°C]	Ri_b
A101	1.153	1.045	114.8	25.19	18.29	16.96	14.19	0.355
A102	0.659	0.432	122.6	63.18	17.68	15.38	12.98	1.851
A103	-99999	-99999	-99999	-99999	-99999	N/A	N/A	N/A
A104	2.830	2.754	63.14	12.70	17.96	N/A	N/A	N/A
A105	2.716	2.682	131.1	9.152	20.67	19.93	17.78	0.037
A106	2.394	2.133	81.94	50.65	18.93	18.26	18.02	0.044
A107	1.917	1.822	163.3	18.12	18.57	17.43	14.82	0.111
A108	3.032	2.977	115.3	10.78	18.0[illegible]	17.04	16.09	0.040
A109	3.005	2.984	84.22	10.33	25.49	24.57	17.87	0.036
A110	2.148	2.104	96.12	21.00	23.51	22.46	18.81	0.081
A111	2.596	2.468	144.2	18.18	N/A	N/A	N/A	N/A
A112	3.419	3.389	157.1	7.796	N/A	N/A	N/A	N/A
A113	3.676	3.579	79.30	13.41	N/A	N/A	N/A	N/A
A114	0.827	0.584	116.6	62.96	17.28	15.84	N/A	0.579
A115	1.611	1.579	85.52	13.62	18.56	15.84	N/A	N/A

Notes:

1. All wind speed and direction measurements are at 10 m, except for Station A115 which is at 30 m.
2. All upper temperature measurements (T_{10m}) are at 10 m as implied by the subscript, except for Station A114 which is at 8 m and Station A115 which is at 30 m.
3. All lower temperature measurements (T_{2m}) are at 2 m as implied by the subscript.
4. Soil temperature measurements (T_{soil}) are a depth of 0.1 m.

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Appendix B Fog-oil Concentration Data

In previous analyses of the fog-oil smoke concentrations (DeVaull, 1990), a uniform correction factor of 3.1 was employed to account for evaporation of oil from the filters. This correction factor was obtained by analyzing 18 samples which were stored in stainless steel tubes instead of filter cassettes. As discussed in DeVaull's report, filters in the stainless steel tubes experience a minimal loss of oil compared with those stored in filter cassettes, thus providing a reasonable basis for estimating oil loss. Initially, the oil loss was assumed to be solely a result of evaporation, but it was later hypothesized that wicking of the oil onto the filter cassette was also responsible for some of the oil loss. Re-examination of the fog-oil data showed that the percentage losses were much lower on heavily exposed filters, and the uniform correction factor of 3.1 was strongly biased by a few filters with the least loading. From this new perspective, a more sophisticated correction scheme was developed which took into account the amount of time the filter spent in the cassette and the amount of oil on the filter. These new concentration estimates are presented here.

Tables B.1 - B.13 present the corrected average fog-oil concentration data for all of the stable and unstable releases. Average concentrations are presented for the 1-m, 2-m and 8-m levels. The 1-m level concentration measurements were only taken at Transect No. 1 for each of the tests.

Table B.1 Average Concentration Data for Unstable Test No. 0921871.

		CONCENTRATION (mg/m^3)		
Transect	Mast	1-m Level	2-m Level	8-m Level
1	1	0.748	--	--
1	2	37.483	--	--
1	3	80.428	--	--
1	4	99.135	--	--
2	1	--	0.286	0.089
2	2	--	--	--
2	3	--	1.717	0.660
2	4	--	1.696	0.754
2	5	--	--	--
2	6	--	0.438	--
3	1	--	0.025	--
3	2	--	0.063	--
3	3	--	0.133	--
3	4	--	0.196	0.256
3	5	--	0.194	0.239
3	6	--	0.181	0.120
3	7	--	0.250	0.313
3	8	--	0.023	0.015
3	9	--	--	0.015
3	10	--	0.039	0.020

Table B.2 Average Concentration Data for Unstable Test No. 0923871.

		CONCENTRATION (mg/m^3)		
Transect	**Mast**	**1-m Level**	**2-m Level**	**8-m Level**
1	1	2.476	--	--
1	2	36.548	--	--
1	3	104.218	--	--
1	4	46.758	--	--
2	1	--	0.528	0.222
2	2	--	0.063	0.563
2	3	--	0.997	0.495
2	4	--	0.825	0.495
2	5	--	0.390	0.301
2	6	--	0.109	0.091
3	1	--	0.113	0.187
3	2	--	0.123	0.143
3	3	--	0.061	0.082
3	4	--	0.177	0.138
3	5	--	0.105	0.059
3	6	--	0.377	0.196
3	7	--	0.288	0.093
3	8	--	0.065	0.048
3	9	--	0.289	0.378
3	10	--	0.272	0.225

Table B.3 Average Concentration Data for Stable Test No. 0925871

		CONCENTRATION (mg/m^3)		
Transect	Mast	1-m Level	2-m Level	8-m Level
1	1	0.288	--	--
1	2	6.028	--	--
1	3	0.224	--	--
2	1	--	0.022	0.032
2	2	--	0.019	0.017
2	3	--	0.053	0.947
2	4	--	3.748	12.164
2	5	--	0.051	0.092
2	6	--	3.301	1.541
2	7	--	0.061	0.051
3	1	--	0.151	0.642
3	2	--	0.122	1.246
3	3	--	0.674	2.141
3	4	--	1.383	4.012
3	5	--	4.461	3.133
3	6	--	4.641	2.282
3	7	--	0.065	0.870
3	8	--	0.260	0.046
4	1	--	1.539	1.129
4	2	--	3.975	0.310
4	3	--	3.656	2.493
4	4	--	4.388	3.980
4	5	--	3.150	3.112
4	6	--	4.336	3.162
5	1	--	0.394	0.562
5	2	--	0.082	0.679
5	3	--	0.593	1.101

Table B.4 Average Concentration Data for Unstable Test No. 0926871

		CONCENTRATION (mg/m^3)		
Transect	Mast	1-m Level	2-m Level	8-m Level
1	1	--	--	--
1	2	--	--	--
1	3	--	--	--
1	4	--	--	--
2	1	--	--	0.114
2	2	--	0.029	1.083
2	3	--	2.608	1.000
2	4	--	1.576	1.429
2	5	--	1.010	0.368
2	6	--	0.784	0.168
3	1	--	0.021	0.048
3	2	--	0.041	0.052
3	3	--	0.263	0.289
3	4	--	0.787	0.464
3	5	--	1.149	0.457
3	6	--	1.177	0.451
3	7	--	0.845	0.572
3	8	--	0.073	0.026
3	9	--	0.549	0.422
3	10	--	0.202	0.213

Table B.5 Average Concentration Data for Stable Test No. 0927871, Transect No. 1.

		CONCENTRATION (mg/m^3)		
Transect	Mast	1-m Level	2-m Level	8-m Level
1	1	2.909	--	--
1	2	19.027	--	--
1	3	2.375	--	--

Table B.6 Average Concentration Data for Stable Test No. 0927872, Transect No. 1.

		CONCENTRATION (mg/m^3)		
Transect	Mast	1-m Level	2-m Level	8-m Level
1	1	2.940	--	--
1	2	67.569	--	--
1	3	3.900	--	--

Table B.7 Average Concentration Data for Stable Test Nos. 0927871 & 0927872 Combined.

		CONCENTRATION (mg/m^3)		
Transect	Mast	1-m Level	2-m Level	8-m Level
1	1	--	--	--
1	2	--	--	--
1	3	--	--	--
2	1	--	0.113	0.139
2	2	--	0.069	0.114
2	3	--	1.006	0.514
2	4	--	2.054	1.850
2	5	--	10.255	8.068
2	6	--	1.267	2.537
2	7	--	0.530	1.339
3	1	--	0.219	0.092
3	2	--	1.033	0.335
3	3	--	1.291	0.163
3	4	--	5.912	1.583
3	5	--	13.166	6.359
3	6	--	9.425	21.410
3	7	--	0.225	7.808
3	8	--	3.598	3.758
4	1	--	3.678	3.766
4	2	--	3.445	1.893
4	3	--	5.356	1.948
4	4	--	6.029	1.572
4	5	--	4.463	3.573
4	6	--	10.734	6.496
5	1	--	1.775	1.545
5	2	--	1.724	1.454
5	3	--	2.492	2.135

Table B.8 Average Concentration Data for Unstable Test No. 0928871.

		CONCENTRATION (mg/m^3)		
Transect	Mast	1-m Level	2-m Level	8-m Level
1	1	12.353	--	--
1	2	50.898	--	--
1	3	7.604	--	--
1	4	0.442	--	--
2	1	--	1.013	1.549
2	2	--	0.229	0.160
2	3	--	0.026	0.102
2	4	--	0.025	0.019
2	5	--	0.035	0.033
2	6	--	--	0.024
3	1	--	0.574	0.289
3	2	--	0.316	0.174
3	3	--	0.035	0.085
3	4	--	0.044	0.050
3	5	--	0.036	0.111
3	6	--	0.021	0.042
3	7	--	0.026	0.064
3	8	--	0.070	0.060
3	9	--	0.082	0.078
3	10	--	0.032	0.029

Table B.9 Average Concentration Data for Stable Test No. 0930871.

		CONCENTRATION (mg/m^3)		
Transect	Mast	1-m Level	2-m Level	8-m Level
1	1	0.700	--	--
1	2	35.845	--	--
1	3	0.654	--	--
2	1	--	0.042	0.031
2	2	--	0.041	0.045
2	3	--	3.952	1.657
2	4	--	10.458	5.491
2	5	--	16.209	3.021
2	6	--	5.577	2.500
2	7	--	0.237	0.327
3	1	--	0.092	0.229
3	2	--	1.357	0.686
3	3	--	2.065	1.352
3	4	--	3.512	3.433
3	5	--	9.517	7.060
3	6	--	6.081	4.553
3	7	--	0.161	3.454
3	8	--	2.586	1.643
4	1	--	1.402	0.558
4	2	--	2.363	0.567
4	3	--	3.387	0.962
4	4	--	4.347	--
4	5	--	3.841	1.705
4	6	--	3.346	2.446
5	1	--	0.240	0.114
5	2	--	0.221	0.368
5	3	--	0.748	0.605
6	1	--	0.111	0.167
6	2	--	0.098	0.179
6	3	--	0.187	0.154
6	4	--	0.023	0.035
6	5	--	0.166	0.151
6	6	--	0.173	0.095
6	7	--	0.166	0.114
6	8	--	--	--
6	9	--	0.159	0.128
6	10	--	0.151	0.148

Table B.10 Average Concentration Data for Stable Test No. 1001871.

		CONCENTRATION (mg/m³)		
Transect	Mast	1-m Level	2-m Level	8-m Level
1	1	1.142	--	--
1	2	18.342	--	--
1	3	0.868	--	--
2	1	--	0.048	0.208
2	2	--	0.036	0.710
2	3	--	1.942	3.038
2	4	--	5.071	3.739
2	5	--	7.010	3.628
2	6	--	3.043	1.408
2	7	--	1.787	0.358
3	1	--	0.222	0.887
3	2	--	0.031	0.188
3	3	--	0.874	1.913
3	4	--	1.759	1.504
3	5	--	4.992	2.934
3	6	--	4.834	2.677
3	7	--	0.059	1.701
3	8	--	2.322	0.275
4	1	--	0.817	0.636
4	2	--	0.571	0.737
4	3	--	0.586	0.722
4	4	--	0.915	1.214
4	5	--	0.940	1.081
4	6	--	1.605	0.571
5	1	--	0.111	0.218
5	2	--	0.377	0.272
5	3	--	0.363	0.417
6	1	--	0.051	0.129
6	2	--	0.049	0.122
6	3	--	0.087	0.068
6	4	--	0.140	0.040
6	5	--	0.099	0.145
6	6	--	0.125	0.125
6	7	--	0.110	0.119
6	8	--	0.072	0.111
6	9	--	0.118	0.105
6	10	--	0.107	0.096

Table B.11 Average Concentration Data for Stable Test No. 1002871.

		CONCENTRATION (mg/m^3)		
Transect	Mast	1-m Level	2-m Level	8-m Level
1	1	1.065	--	--
1	2	15.988	--	--
1	3	0.718	--	--
2	1	--	0.123	0.104
2	2	--	0.091	0.052
2	3	--	2.472	0.667
2	4	--	8.577	10.471
2	5	--	10.953	10.536
2	6	--	15.379	12.602
2	7	--	4.184	6.087
3	1	--	0.047	0.071
3	2	--	0.242	0.011
3	3	--	2.230	0.496
3	4	--	2.518	1.801
3	5	--	8.696	5.523
3	6	--	12.121	5.391
3	7	--	0.123	8.625
3	8	--	7.086	4.743
4	1	--	0.446	0.109
4	2	--	1.029	0.217
4	3	--	2.896	0.647
4	4	--	2.739	0.856
4	5	--	6.337	1.659
4	6	--	5.732	2.798
5	1	--	0.233	0.205
5	2	--	0.229	0.072
5	3	--	0.564	0.638

Table B.12 Average Concentration Data for Unstable Test No. 1002872.

		CONCENTRATION (mg/m^3)		
Transect	Mast	1-m Level	2-m Level	8-m Level
1	1	25.271	--	--
1	2	75.456	--	--
1	3	78.309	--	--
1	4	9.199	--	--
2	1	--	0.701	1.596
2	2	--	1.041	1.192
2	3	--	0.759	1.087
2	4	--	0.215	0.334
2	5	--	0.110	0.111
2	6	--	0.084	0.113
3	1	--	0.404	0.348
3	2	--	0.431	0.439
3	3	--	0.137	0.118
3	4	--	0.295	0.349
3	5	--	0.266	0.239
3	6	--	0.188	0.108
3	7	--	0.115	0.118
3	8	--	0.108	0.092
3	9	--	0.101	0.098
3	10	--	0.078	0.088

Table B.13 Average Concentration Data for Stable Test No. 1003871.

		CONCENTRATION (mg/m^3)		
Transect	Mast	1-m Level	2-m Level	8-m Level
1	1	0.698	--	--
1	2	12.646	--	--
1	3	0.655	--	--
2	1	--	0.037	0.053
2	2	--	0.047	0.063
2	3	--	0.050	0.158
2	4	--	1.898	0.508
2	5	--	6.588	5.479
2	6	--	0.025	3.618
2	7	--	0.037	0.029
3	1	--	0.060	0.025
3	2	--	0.060	0.036
3	3	--	0.073	0.071
3	4	--	0.079	0.085
3	5	--	0.073	0.115
3	6	--	3.081	6.006
3	7	--	0.291	3.440
3	8	--	1.109	3.302
4	1	--	0.112	0.093
4	2	--	0.293	0.422
4	3	--	1.169	1.502
4	4	--	2.877	3.387
4	5	--	3.365	3.015
4	6	--	2.549	3.092
5	1	--	0.389	0.372
5	2	--	0.349	0.369
5	3	--	0.521	0.482
6	1	--	0.127	0.146
6	2	--	0.155	0.071
6	3	--	0.162	0.056
6	4	--	0.188	0.079
6	5	--	0.142	0.044
6	6	--	0.183	0.188
6	7	--	0.146	0.214
6	8	--	0.179	0.209
6	9	--	0.188	0.195
6	10	--	0.200	0.201

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